Neutron Stars as Dark Matter Laboratories

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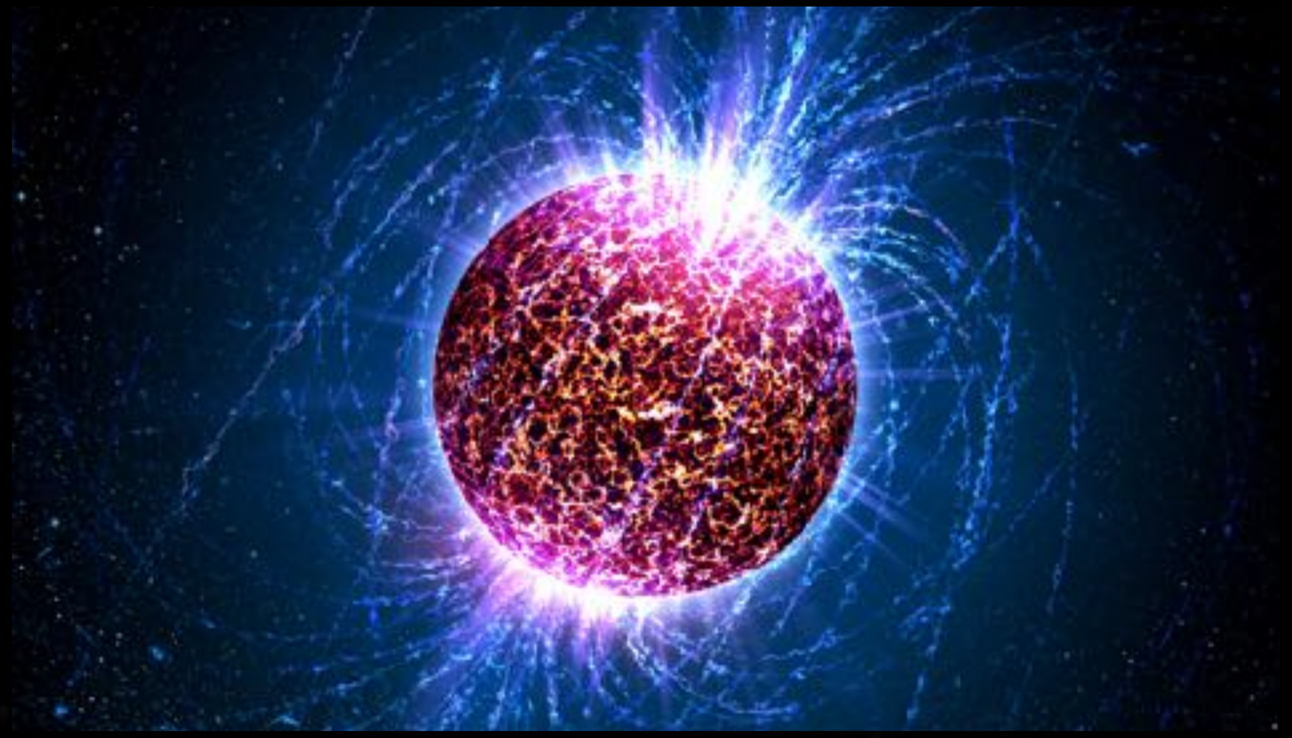
INSTITUTE for NUCLEAR THEORY
U.S. DEPARTMENT OF ENERGY Office of Science
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER
NSF

Neutron Stars and Big Questions



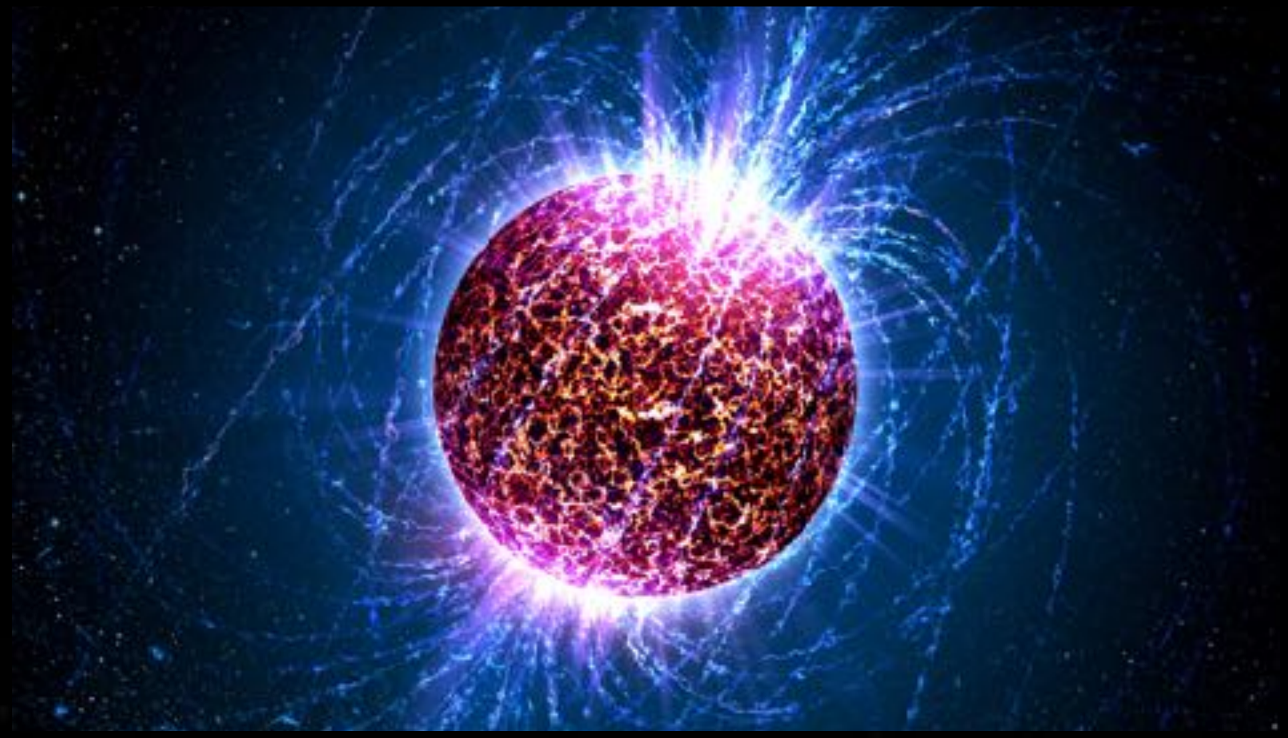
Nature of matter at extreme density?

Origin of cosmic explosions?

Synthesis of heavy elements?

Nature of dark matter?

Neutron Stars and Big Questions



Nature of matter at extreme density?

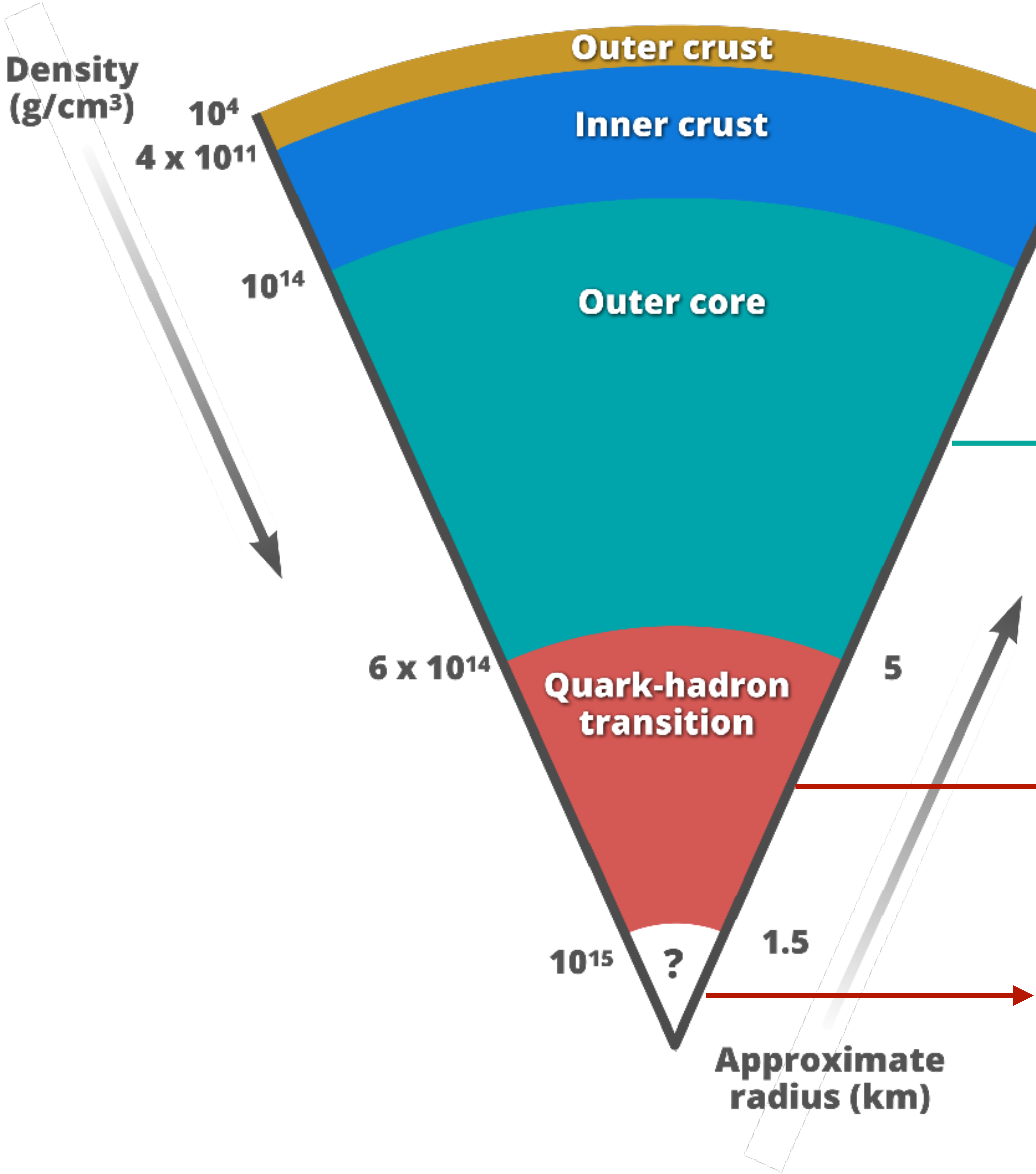
Origin of cosmic explosions?

Synthesis of heavy elements?

Nature of dark matter?

Measuring and interpreting neutron star properties has far reaching implications.

Inside Neutron Stars



Nuclei and relativistic electrons.

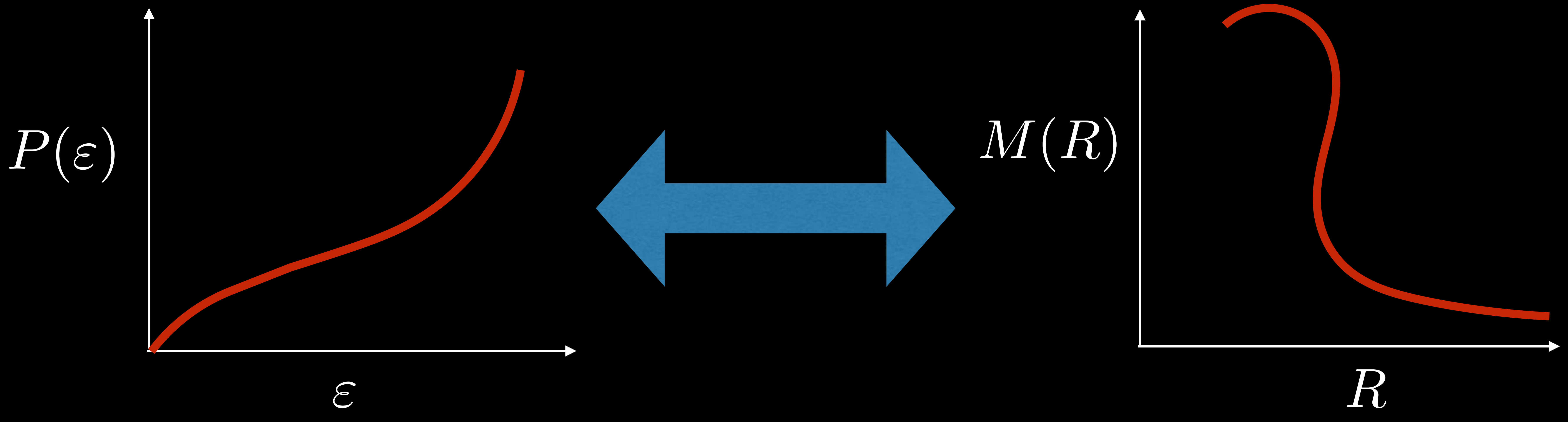
Neutron-rich nuclei, relativistic electrons, superfluid neutrons

Neutrons (~ 90%), protons, relativistic electrons, muons. Description in terms of baryons remains useful. Superfluid neutrons & superconducting protons.

Complex strongly interacting relativistic matter. Description not simple in terms of either baryons or quarks. Quarkyonic Matter?

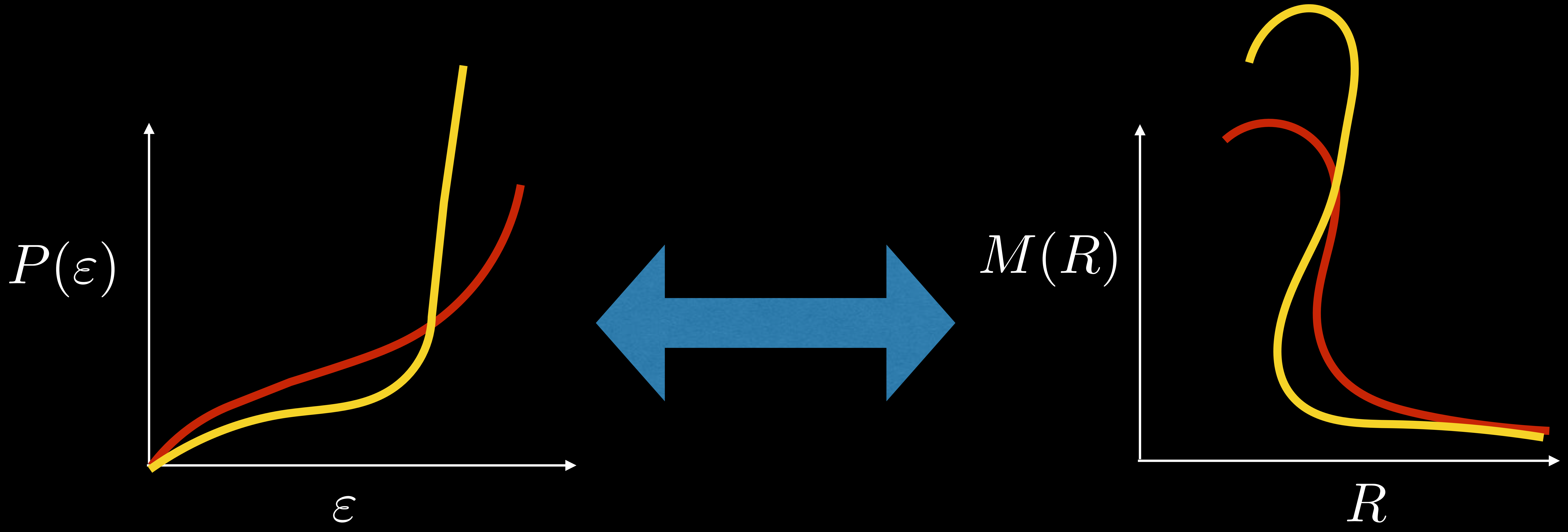
Ordered quark matter? color superconductor?

Equation of State and Neutron Star Structure



$$P(\varepsilon) + \text{Gen.Rel.} = M(R)$$

Equation of State and Neutron Star Structure



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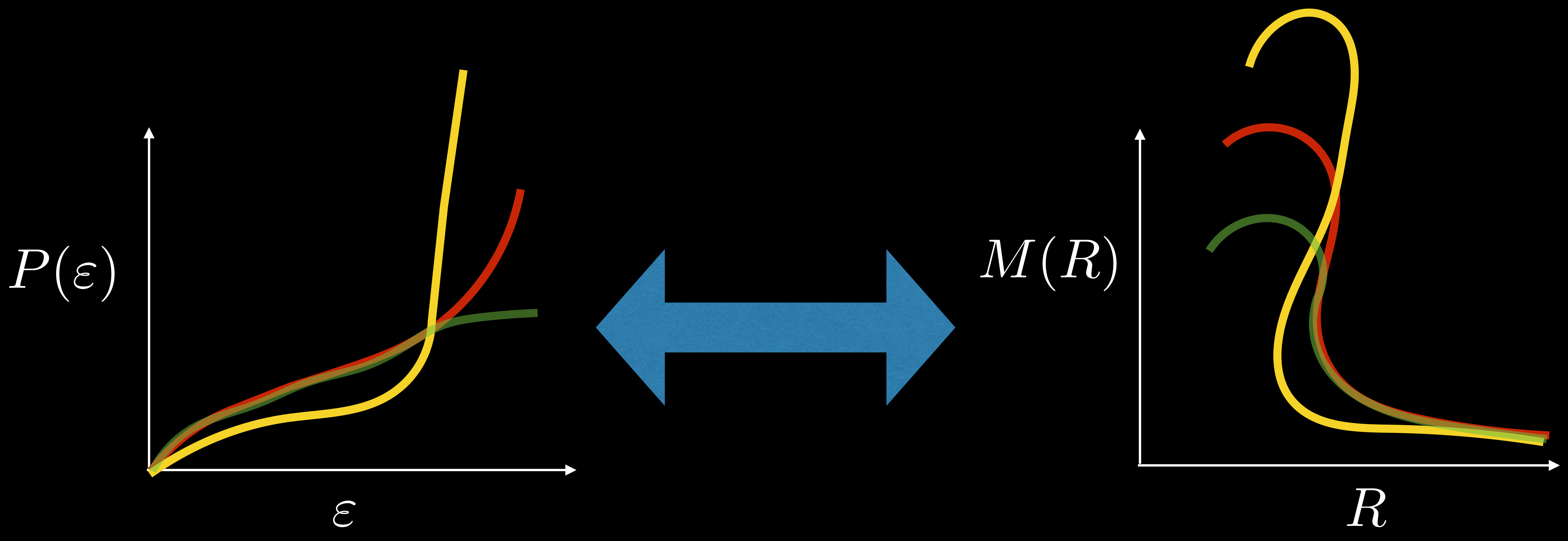

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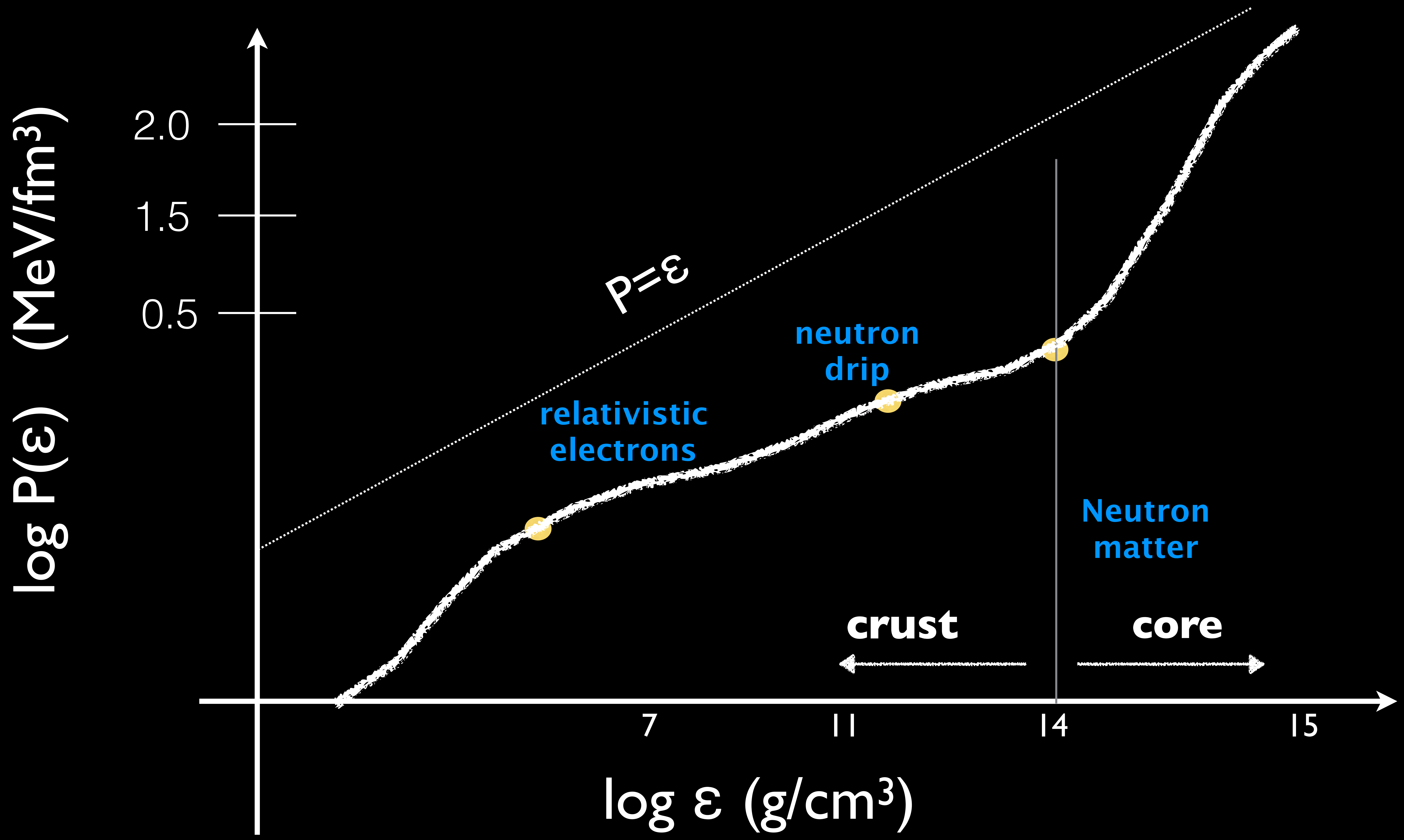
Pressure v/s Energy Density (EoS)



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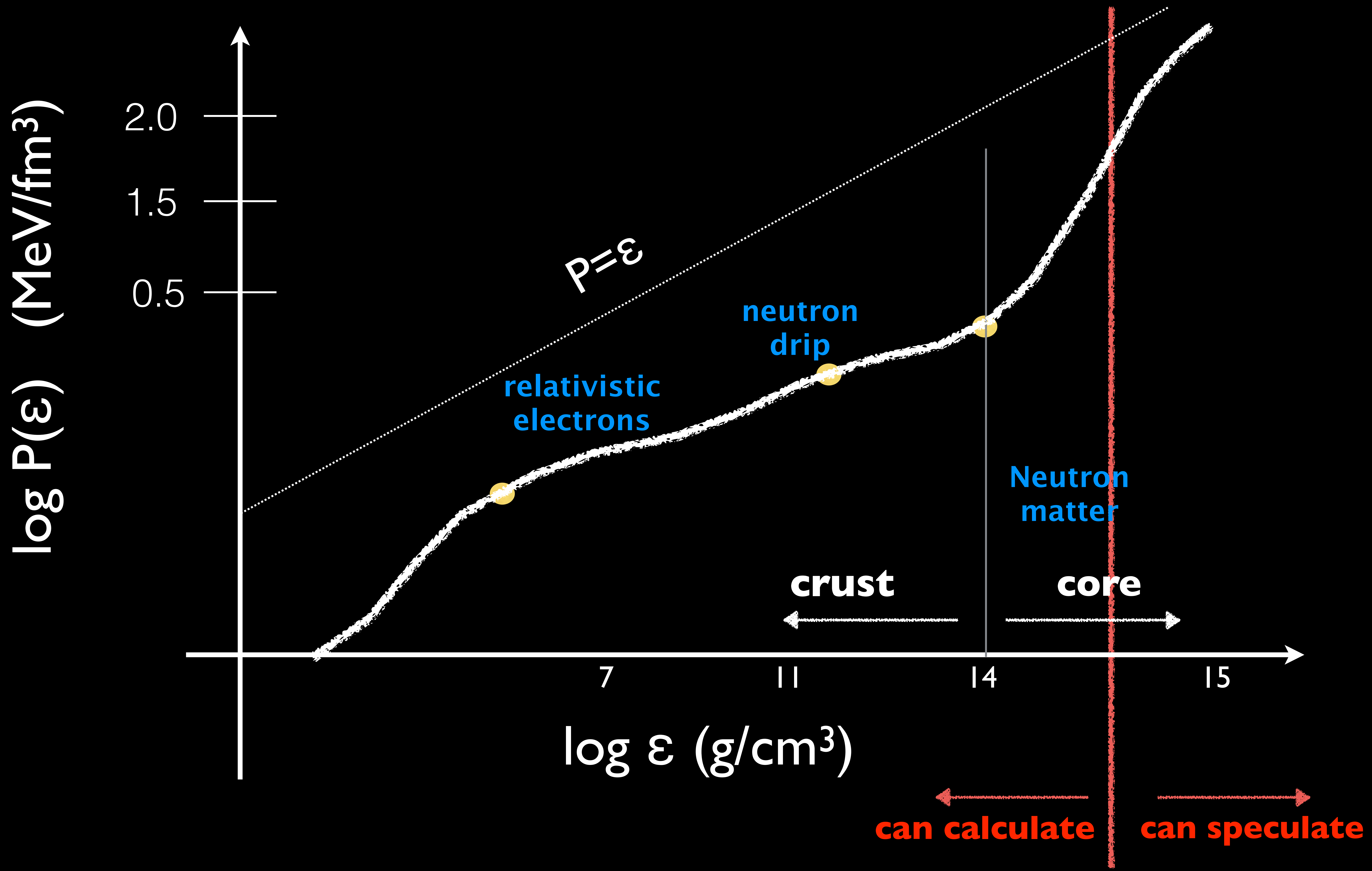

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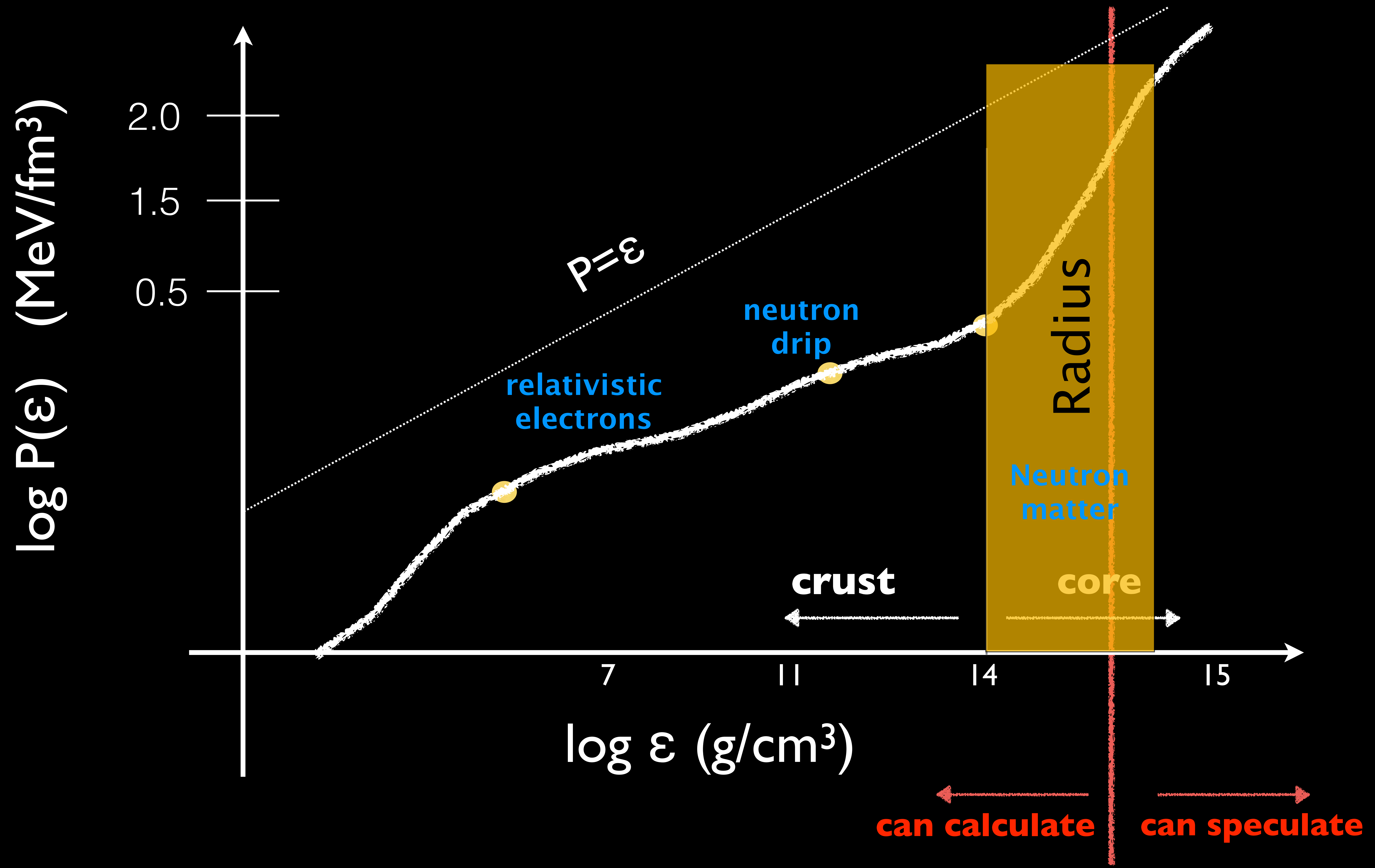

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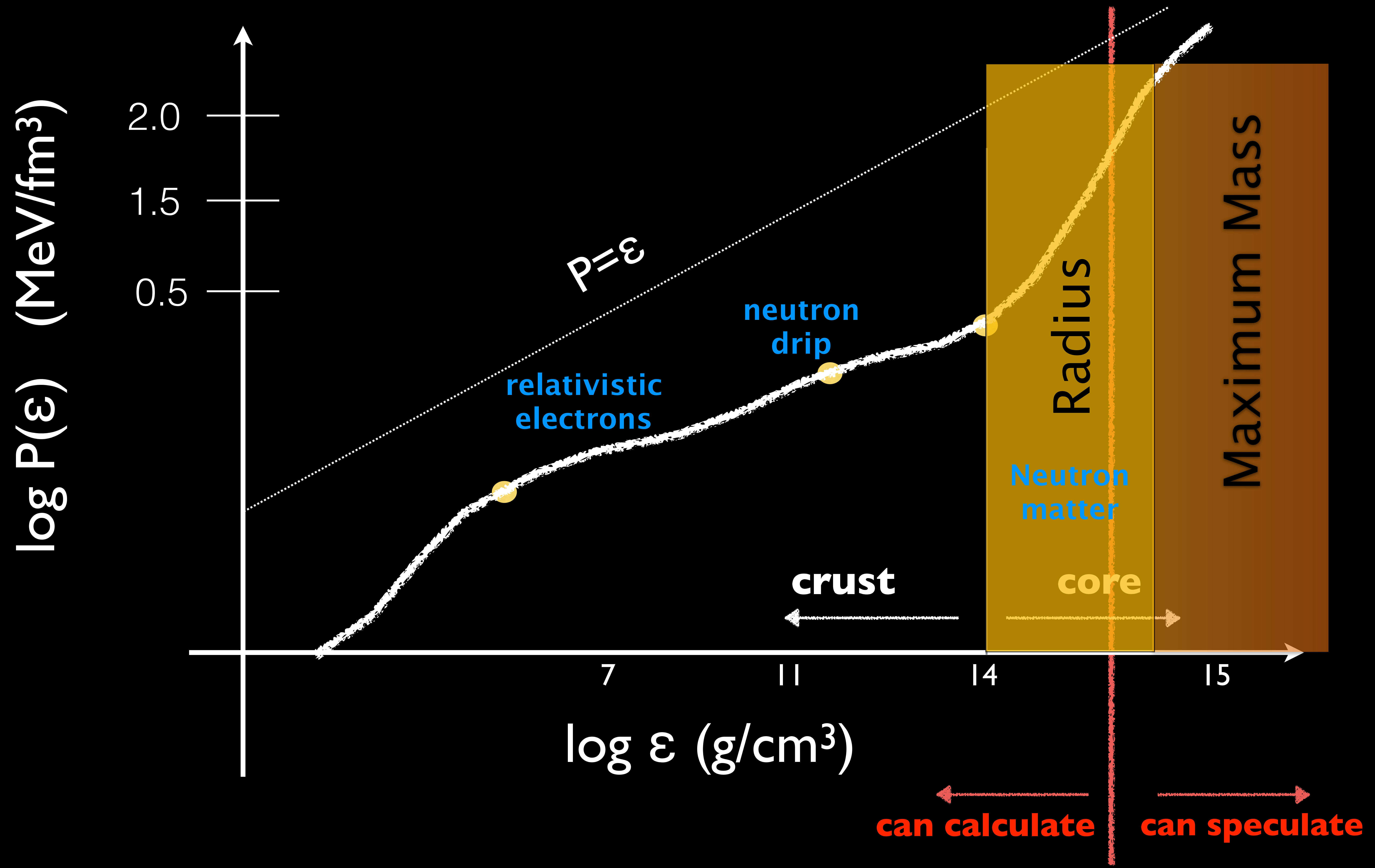
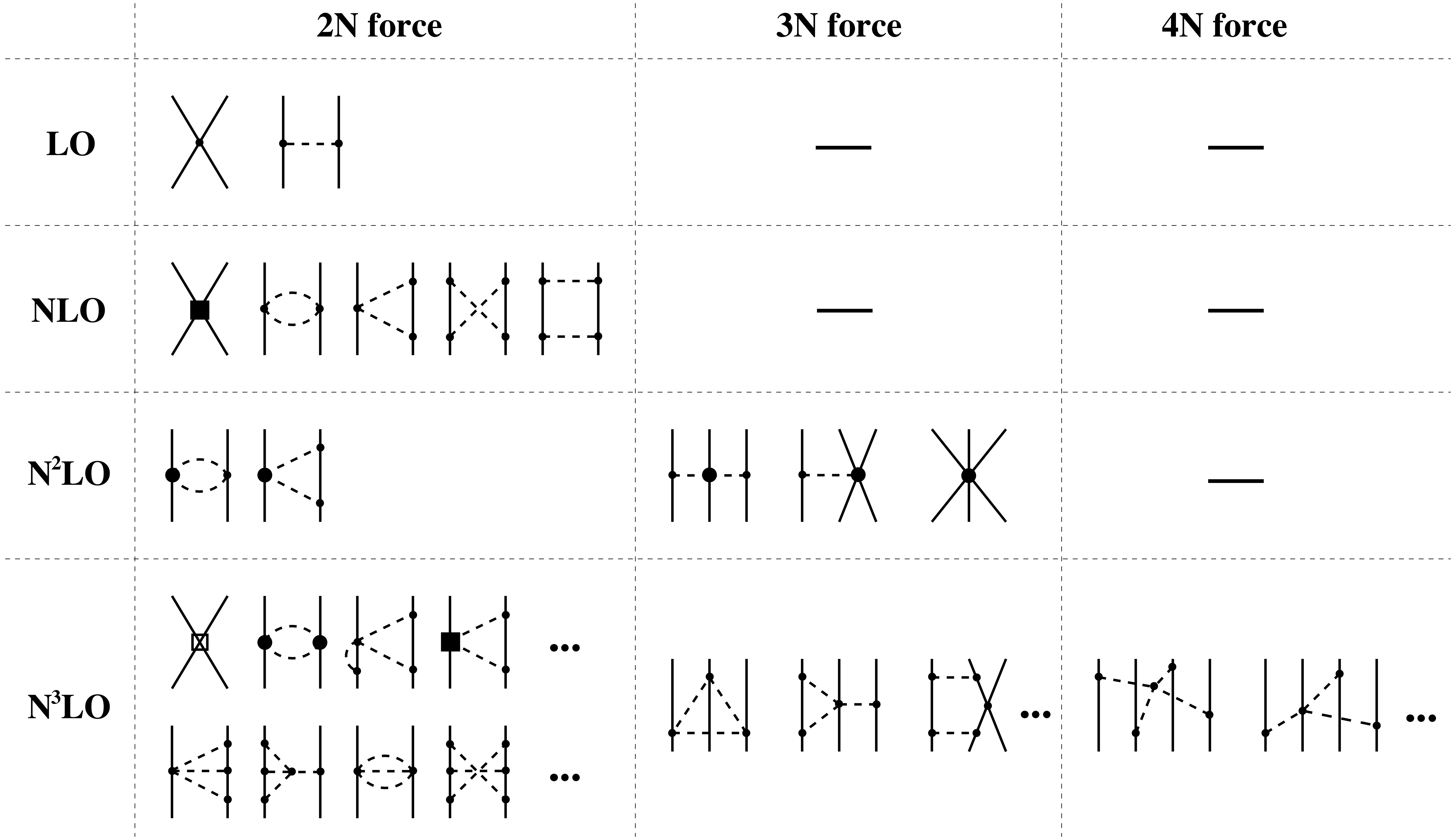
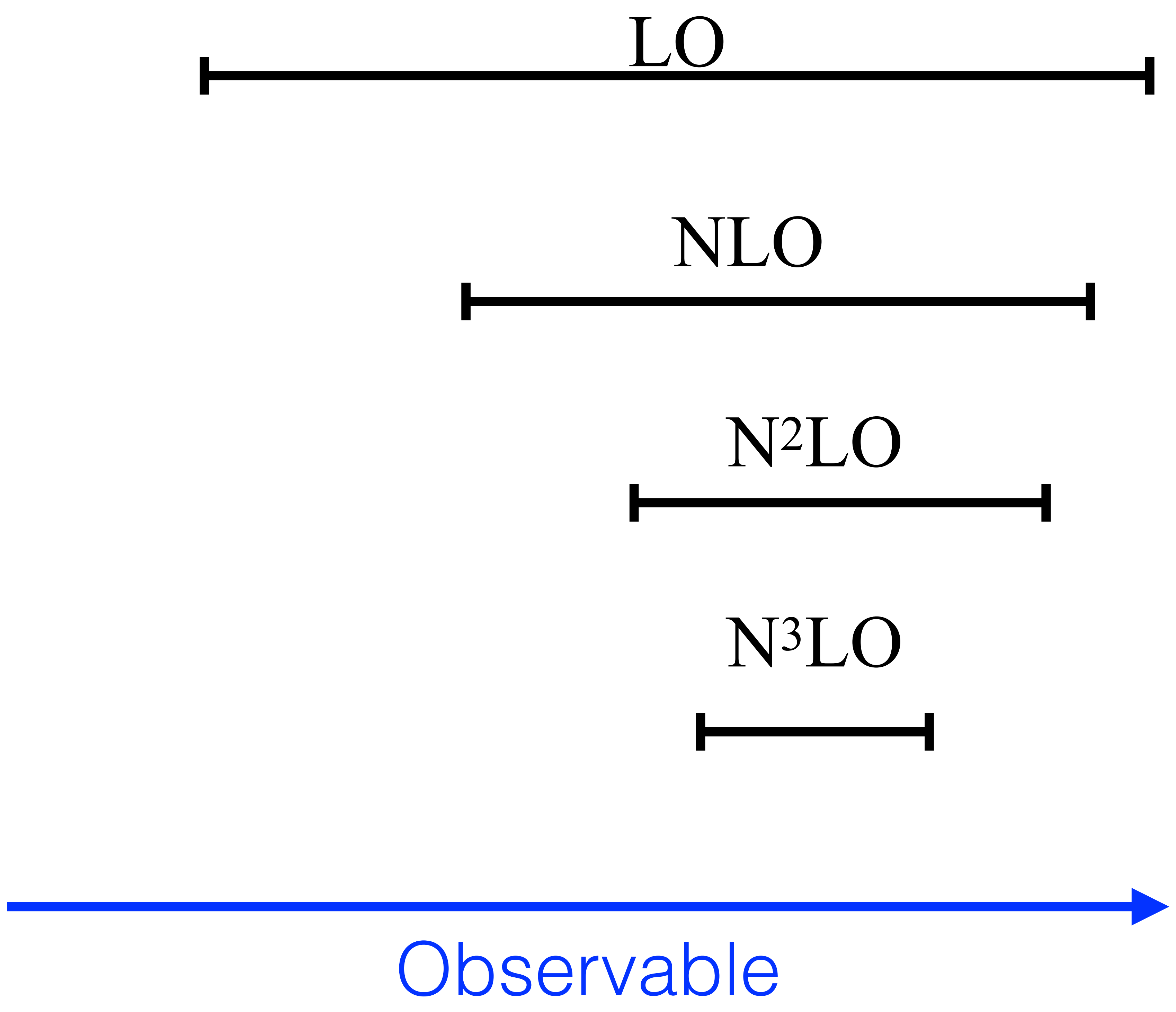


Nuclear Forces from Effective Field Theory (EFT)

EFT Hamiltonians organizes operators in powers of the momentum: $\frac{Q}{\Lambda_B}$





Allows for error estimation*. Provides guidance for the structure of three and many-body forces.

Beane, Bedaque, Epelbaum, Kaplan, Machliedt, Meisner, Phillips, Savage, **van Klock**, **Weinberg,** Wise ..

Equation of State of Dense Nuclear Matter

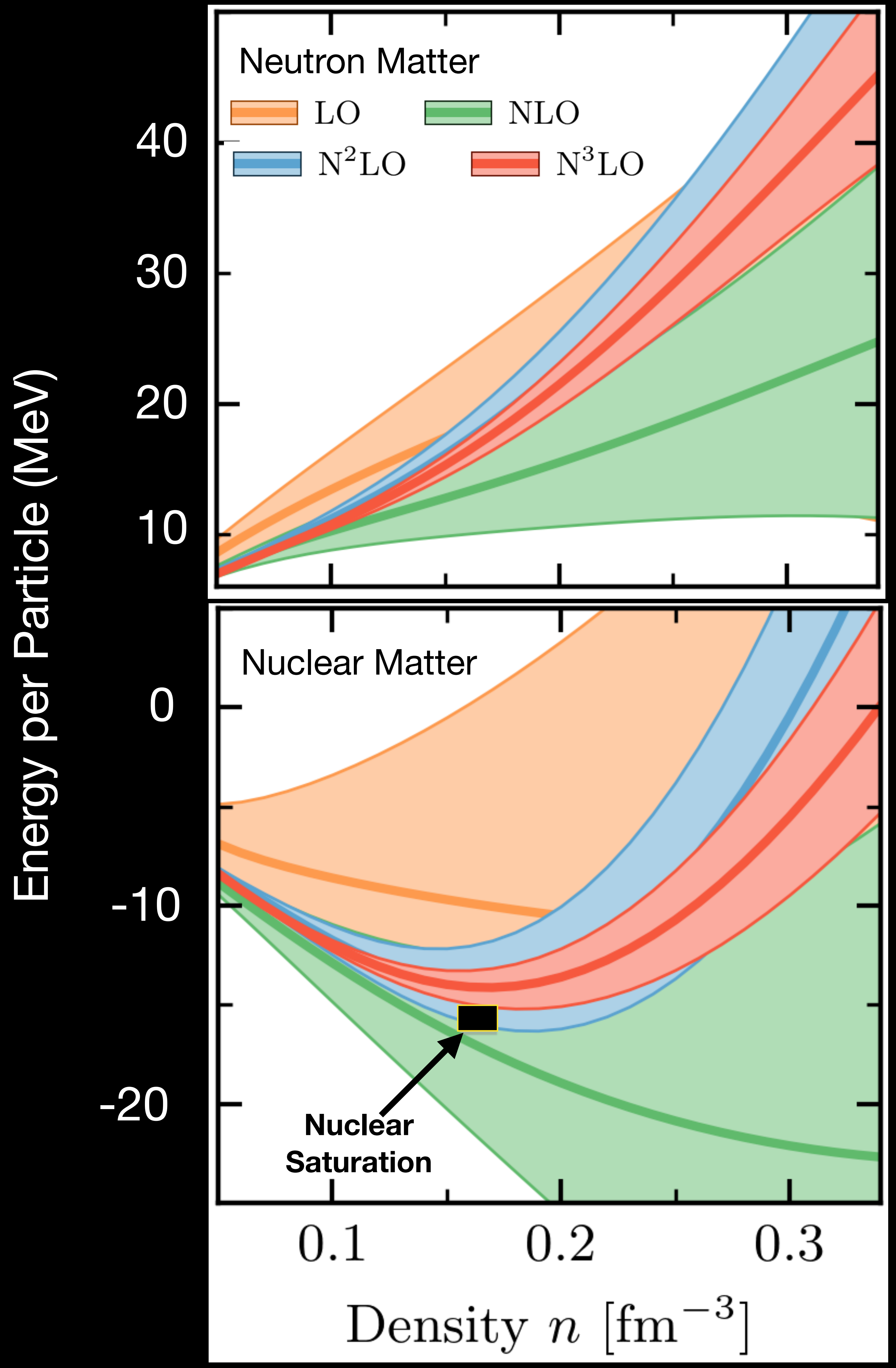
Quantum many-body calculations of neutron matter and nuclear matter using EFT potentials show convergence up to about twice nuclear saturation density.

Many-body perturbation theory and Quantum Monte Carlo methods have both been employed to calculate the energy on dense neutron matter.

Hebeler and Schwenk (2009), Gandolfi, Carlson, Reddy (2010), Gezerlis et al. (2013), Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Hagen et al. (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014), Tews et al. (2018), Drischler et al., (2020).

Drischler et al. used Bayesian methods to systematically estimate the EFT truncation errors in neutron and nuclear matter.

Drischler, Furnstahl, Melendez, Phillips, (2020).



Drischler et al., (2020).

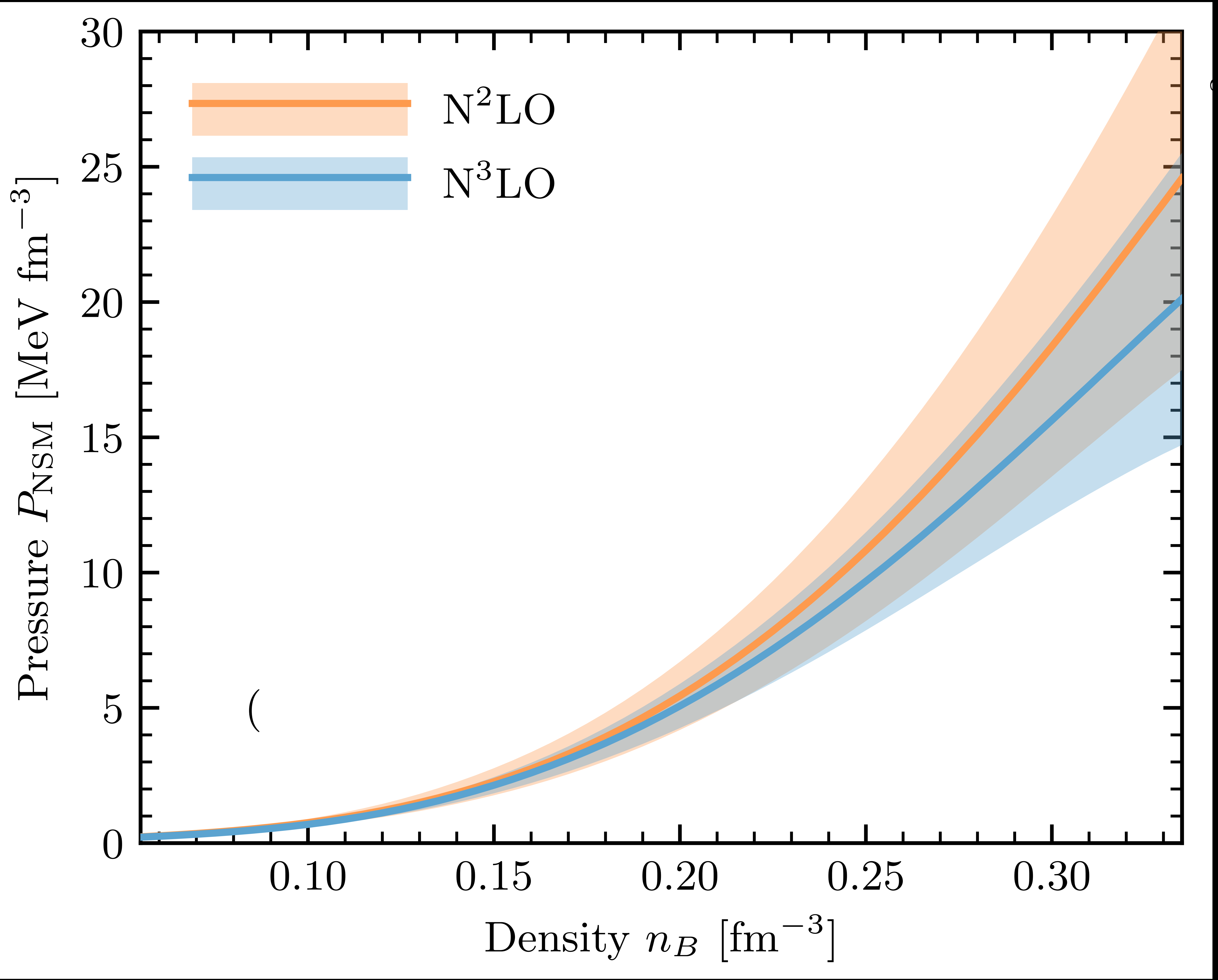
Equation of State of Neutron Star Matter

In neutron stars, matter is in equilibrium with respect to weak interactions and contains a small fraction (about 5-10%) of protons, electrons and muons:

Many-body perturbation theory and Bayesian estimates of the EFT truncation errors predict:

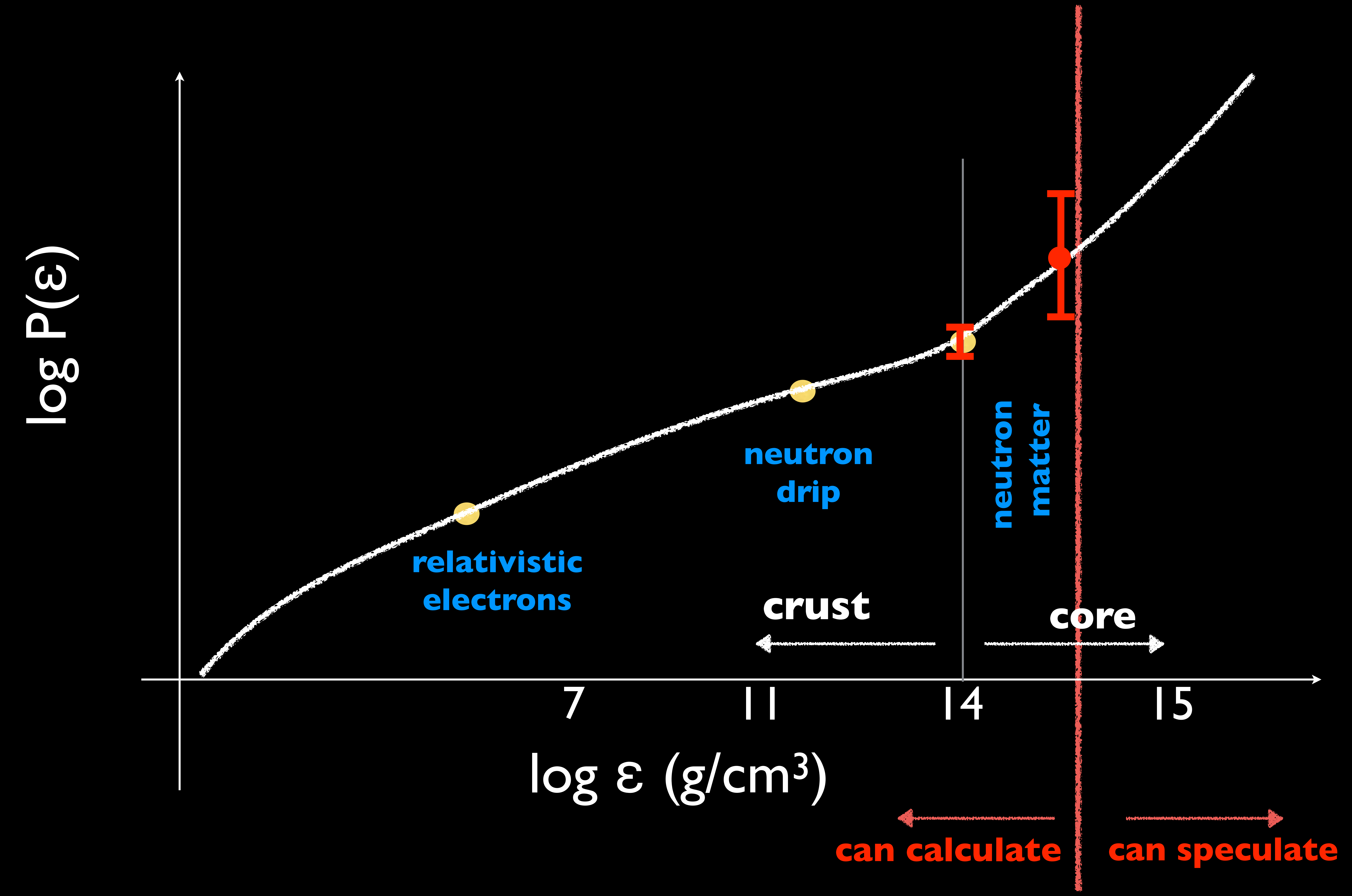
$$P_{\rm NSM}(n_B = 0.16\ {\rm fm}^{-3}) = 3.0 \pm 0.2\ {\rm MeV/fm}^3$$

$$P_{\rm NSM}(n_B = 0.34\ {\rm fm}^{-3}) = 20.0 \pm 5\ {\rm MeV/fm}^3$$



Drischler, Han, Lattimer, Prakash, Reddy, Zhao (2020)

General Constraints on the Equation of State



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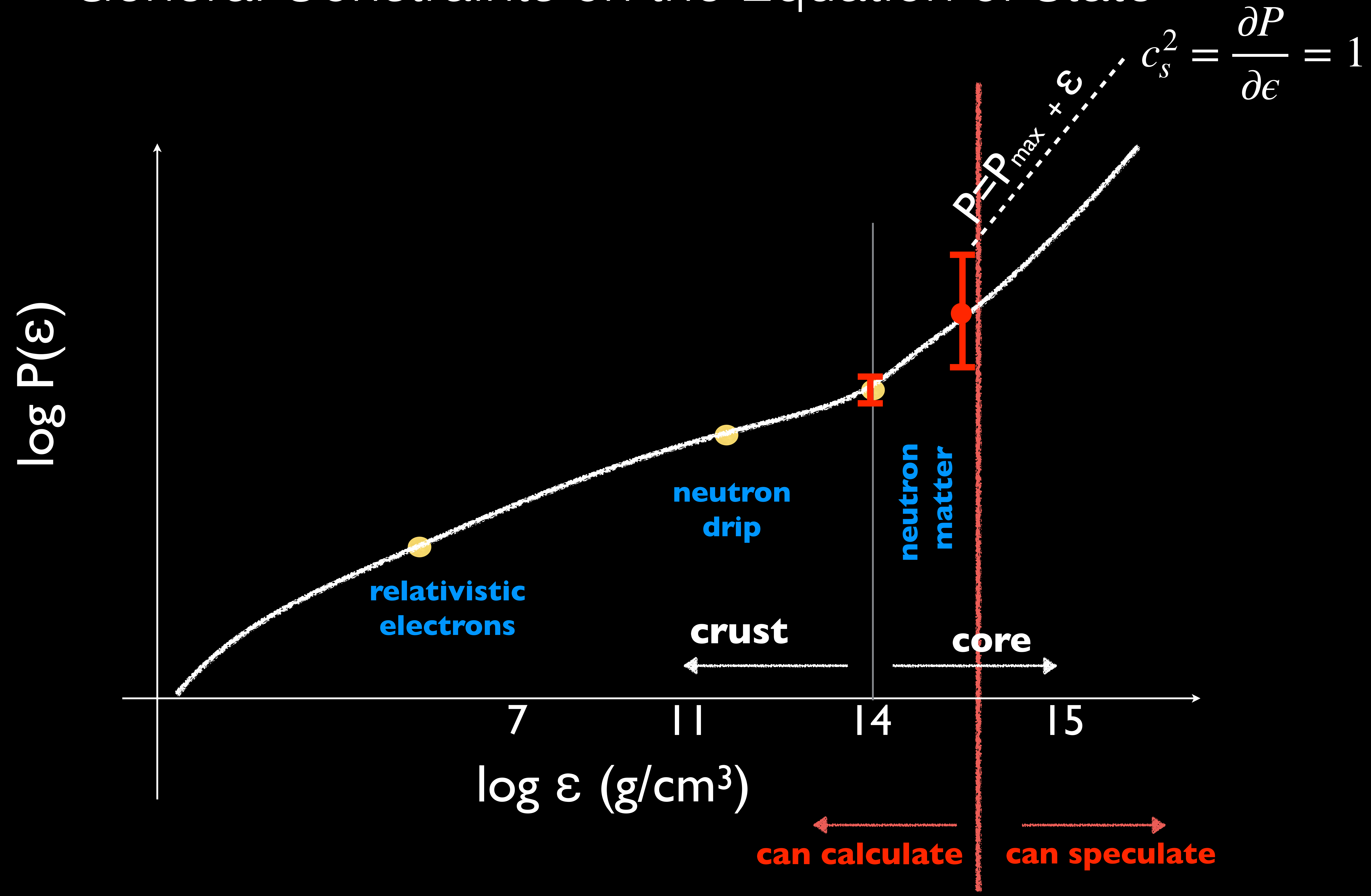

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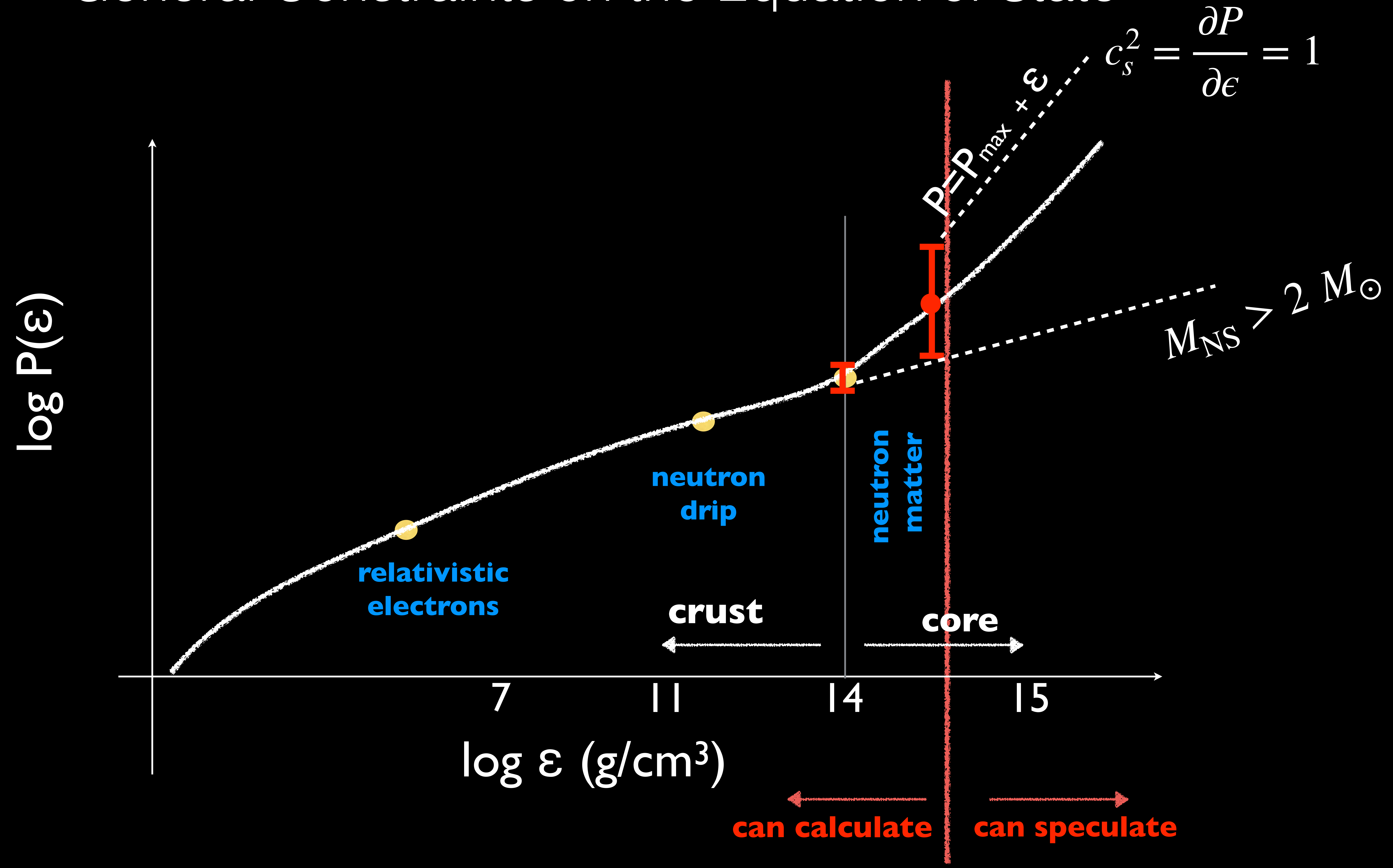
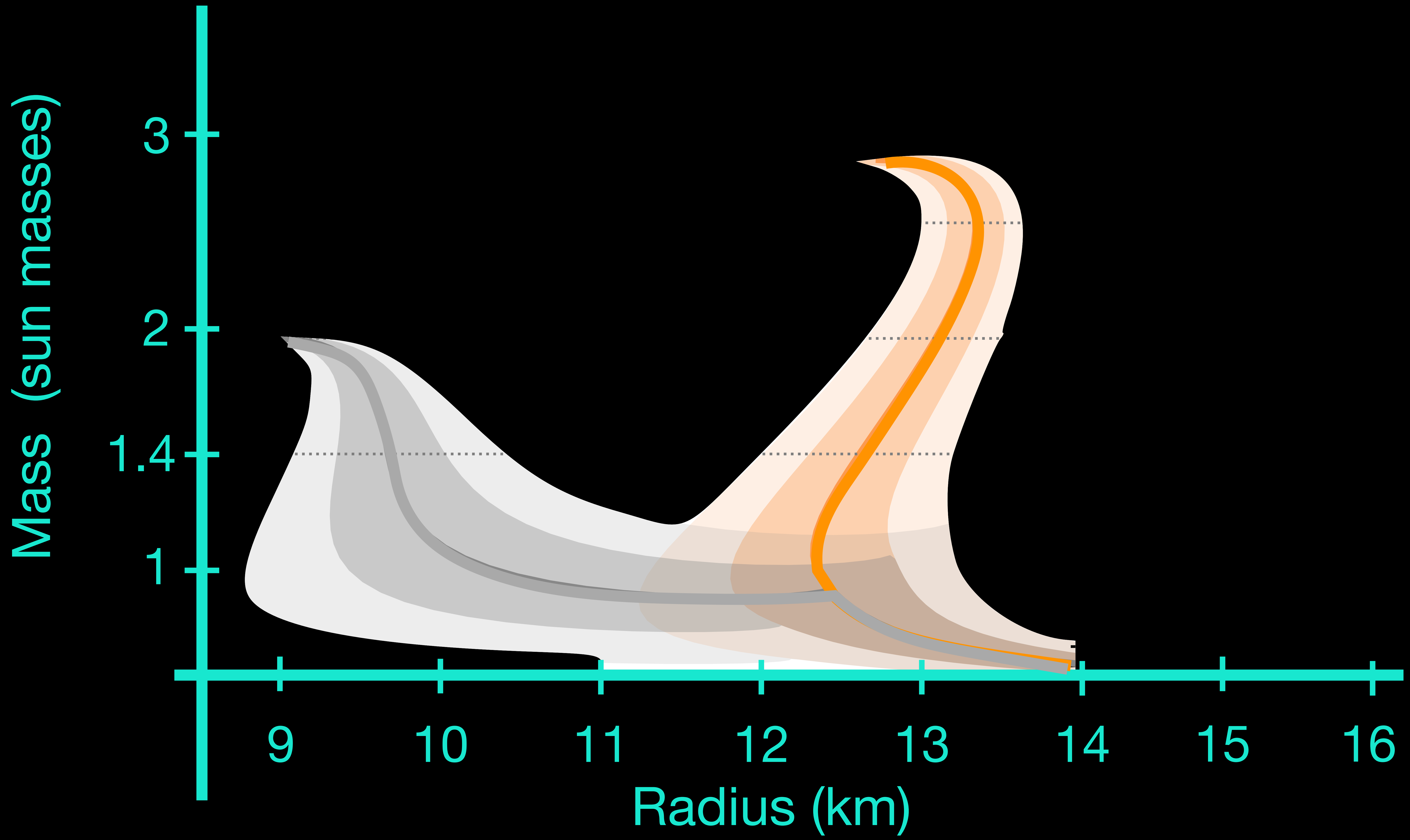


Robust Bounds on Neutron Star Radii

- EFT calculations predict a relatively soft EOS in the neutron star's outer core. Extreme extrapolations place robust bounds on NS radii.

- Neutron star radii are very likely to be in the range of 11-13 km.

- R <11 km or R > 12 km both require regions of the NS with $c_s = c$.



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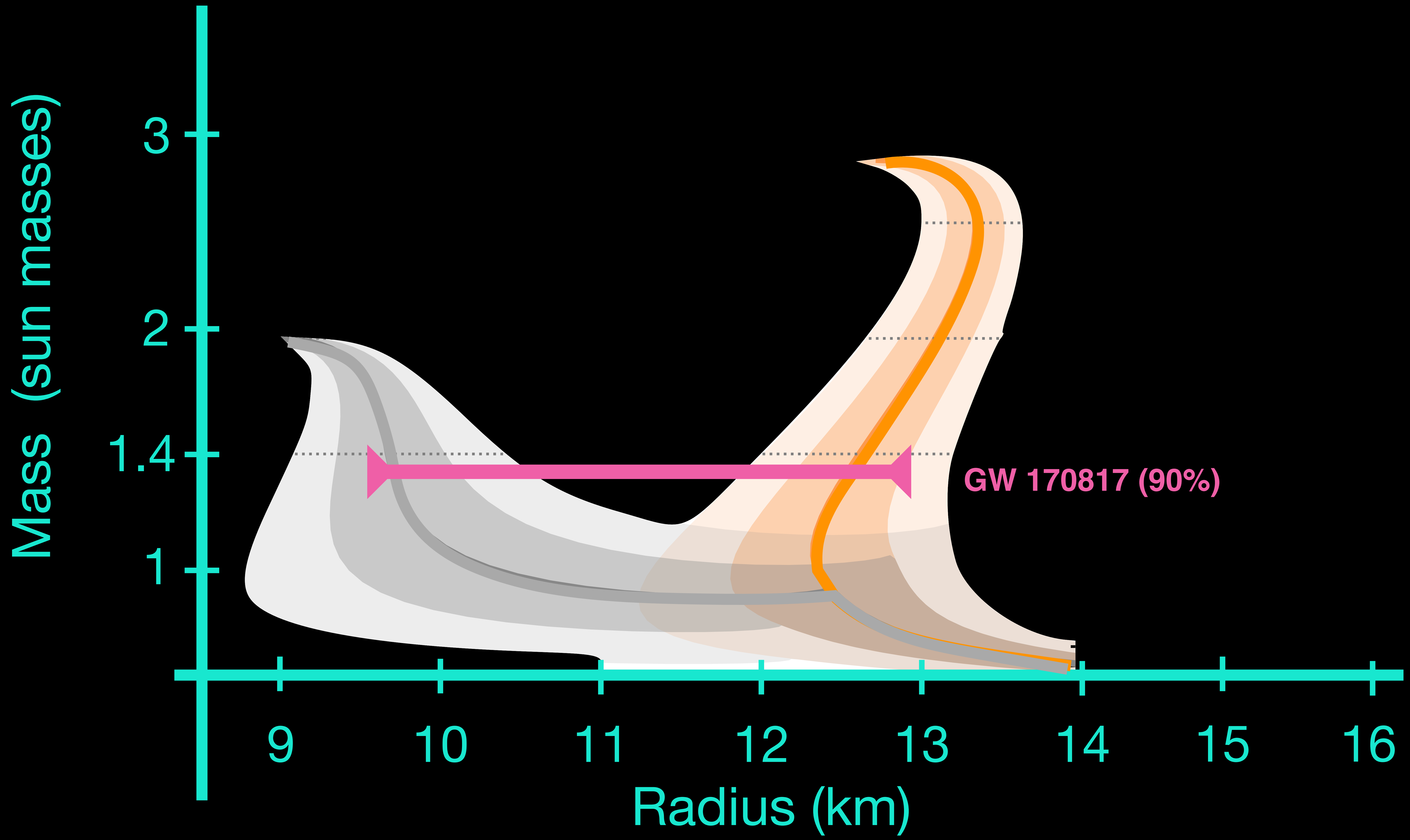

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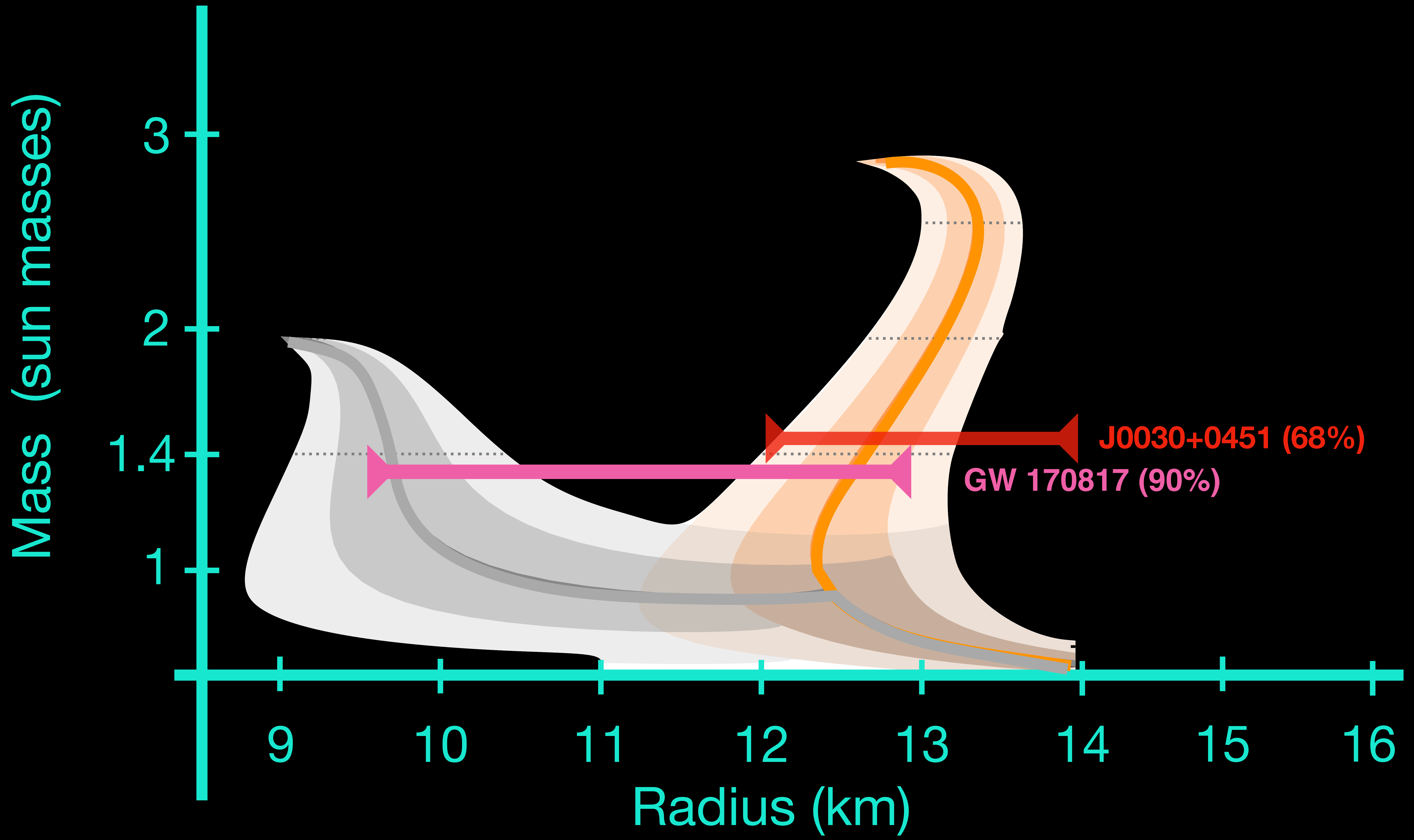

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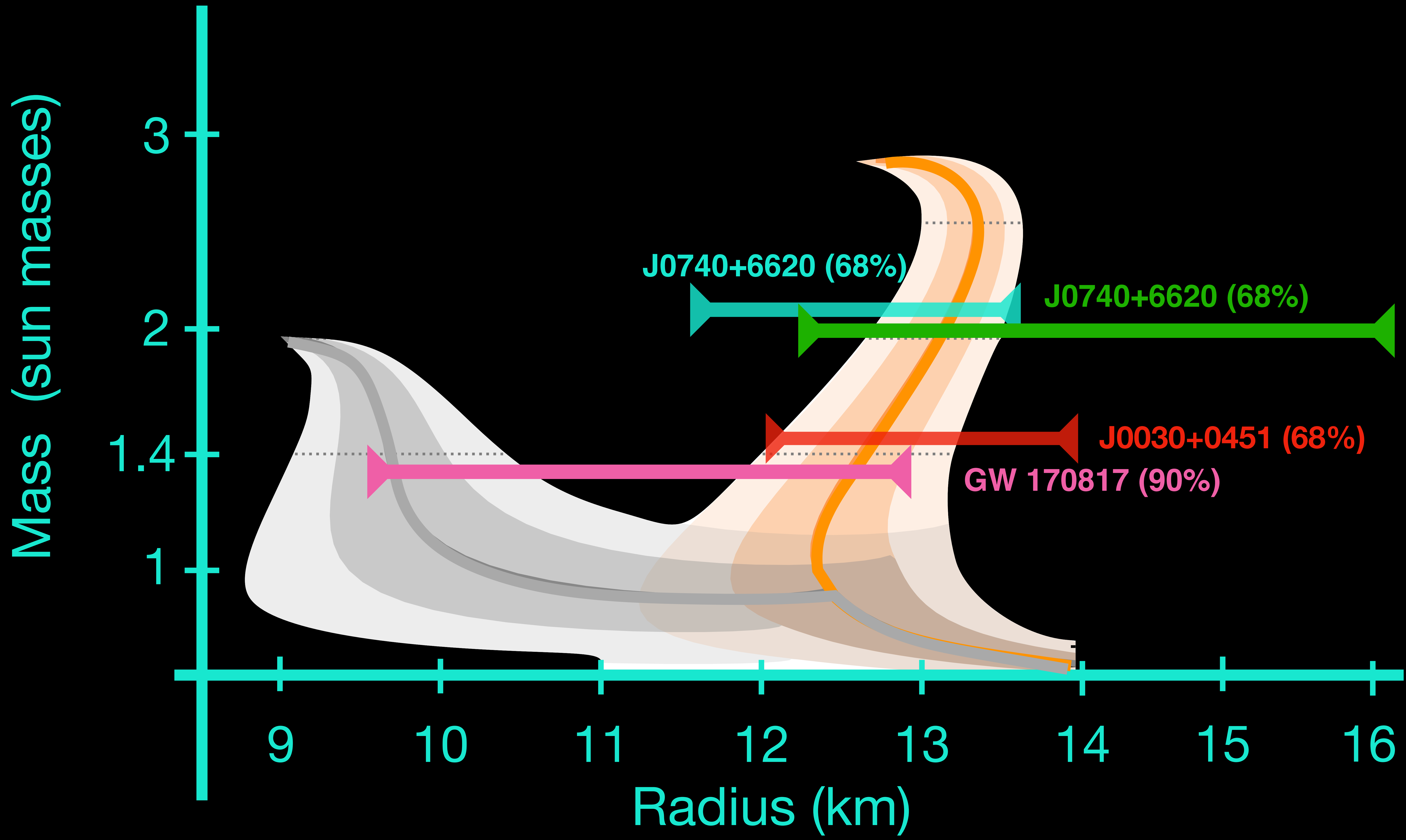
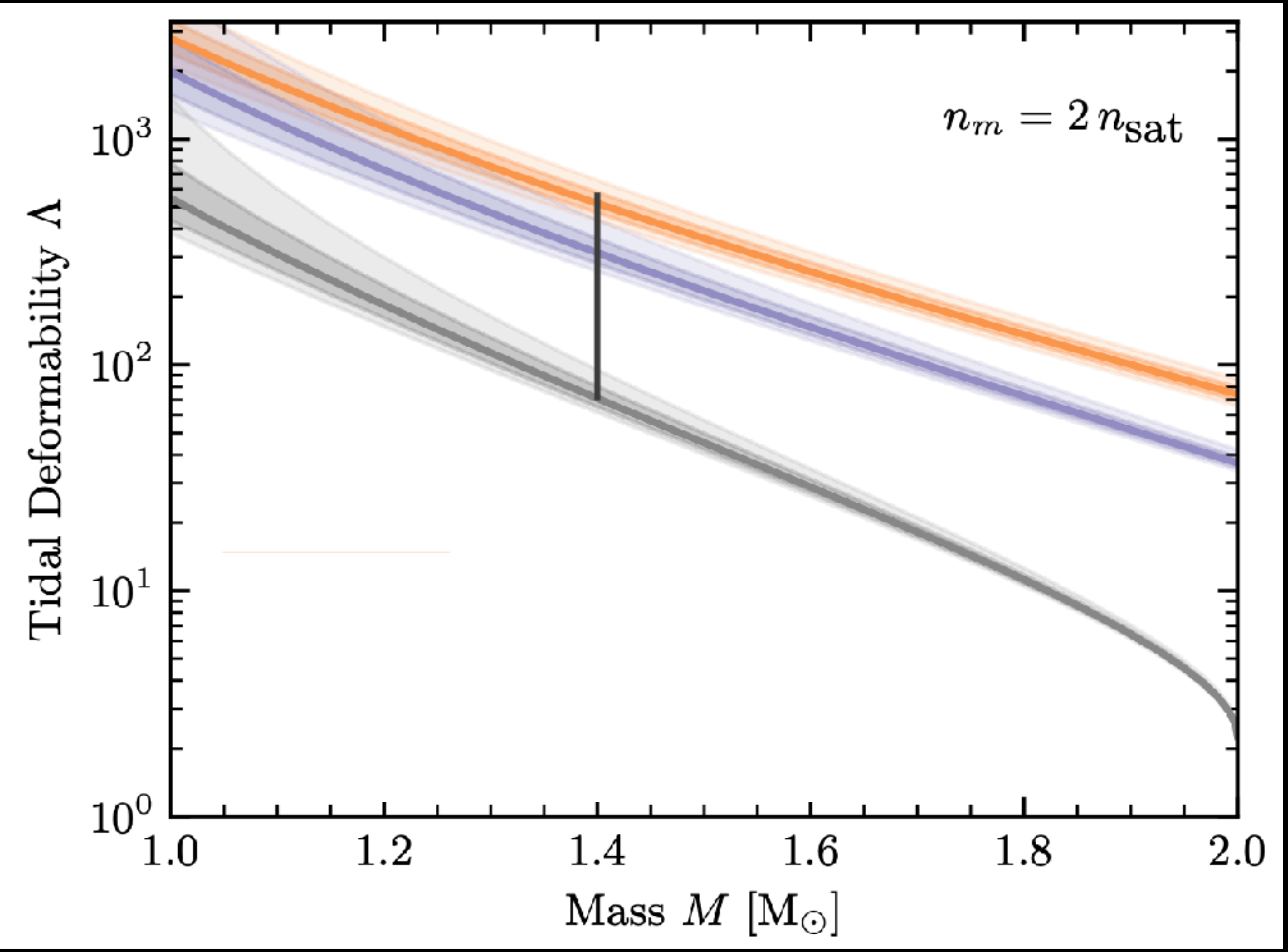
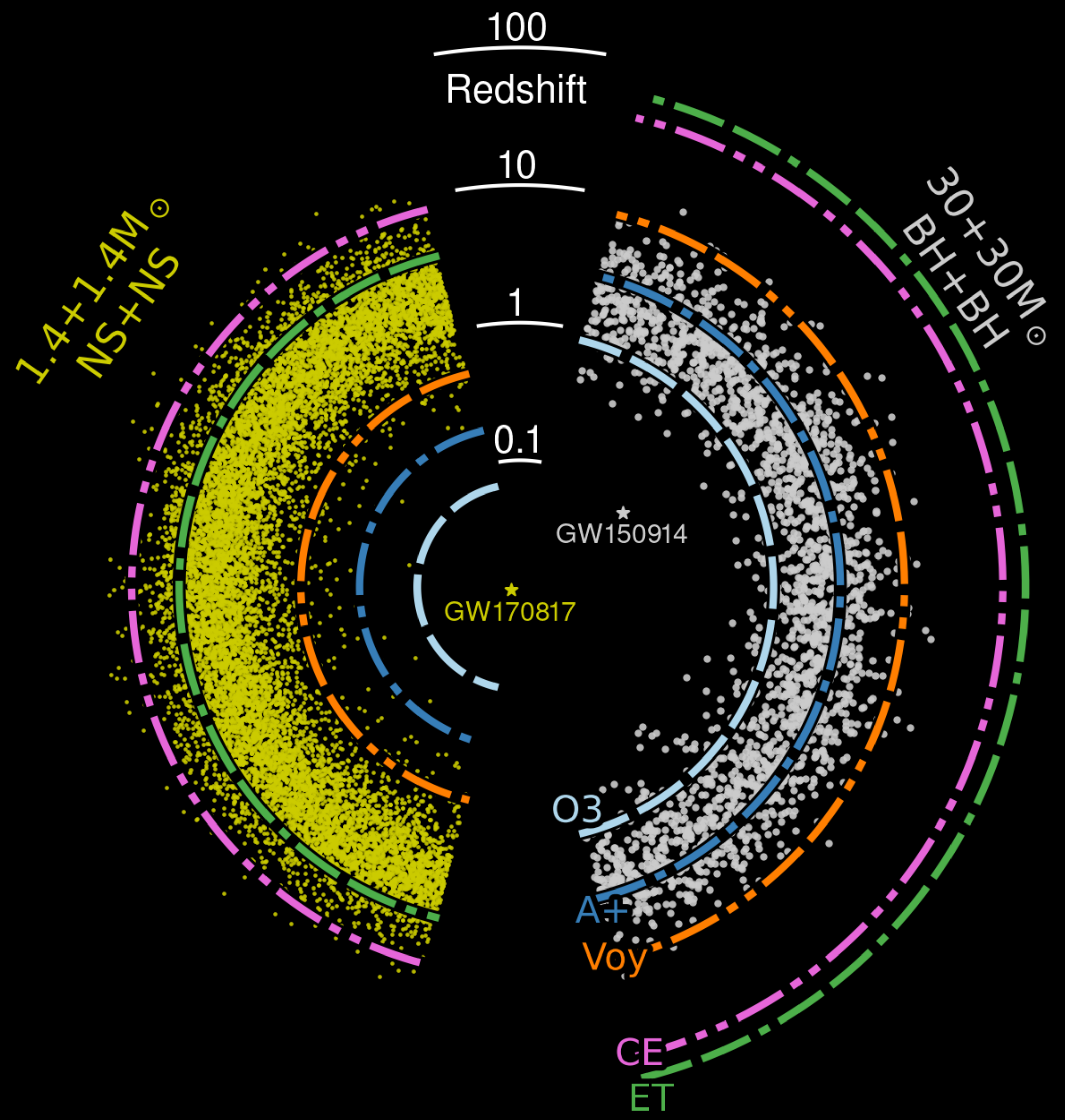


Bounds on the Tidal Deformability & Compact Object Populations





Cosmic Explorer and Einstein Telescope are expected to observe 300,000 BNS/year!

Drischler, Han, Lattimer, Prakash, Reddy, Zhao (2020)

A Horizon Study for Cosmic Explorer: Science, Observatories, and Community https://arxiv.org/abs/2109.09882

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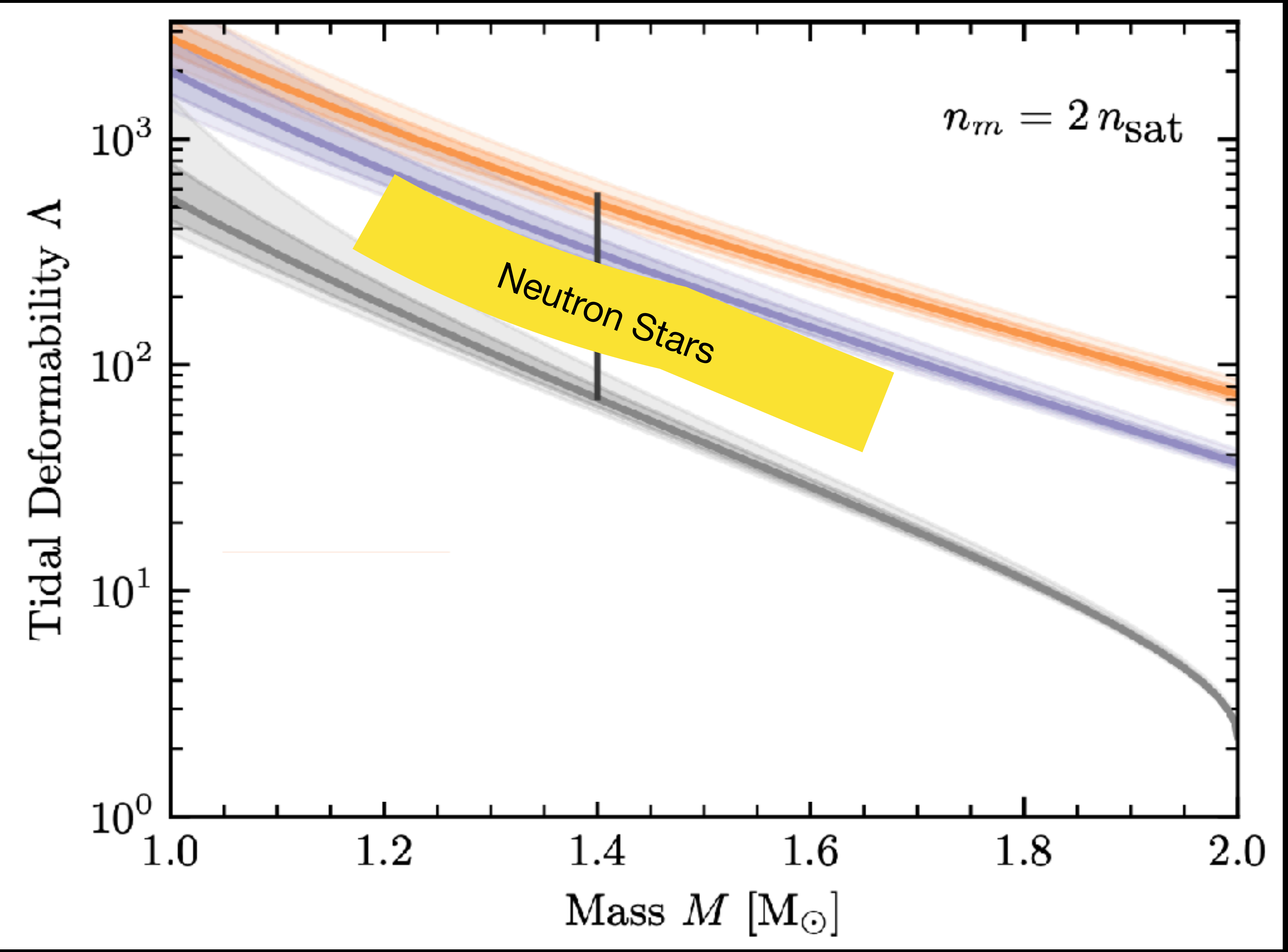

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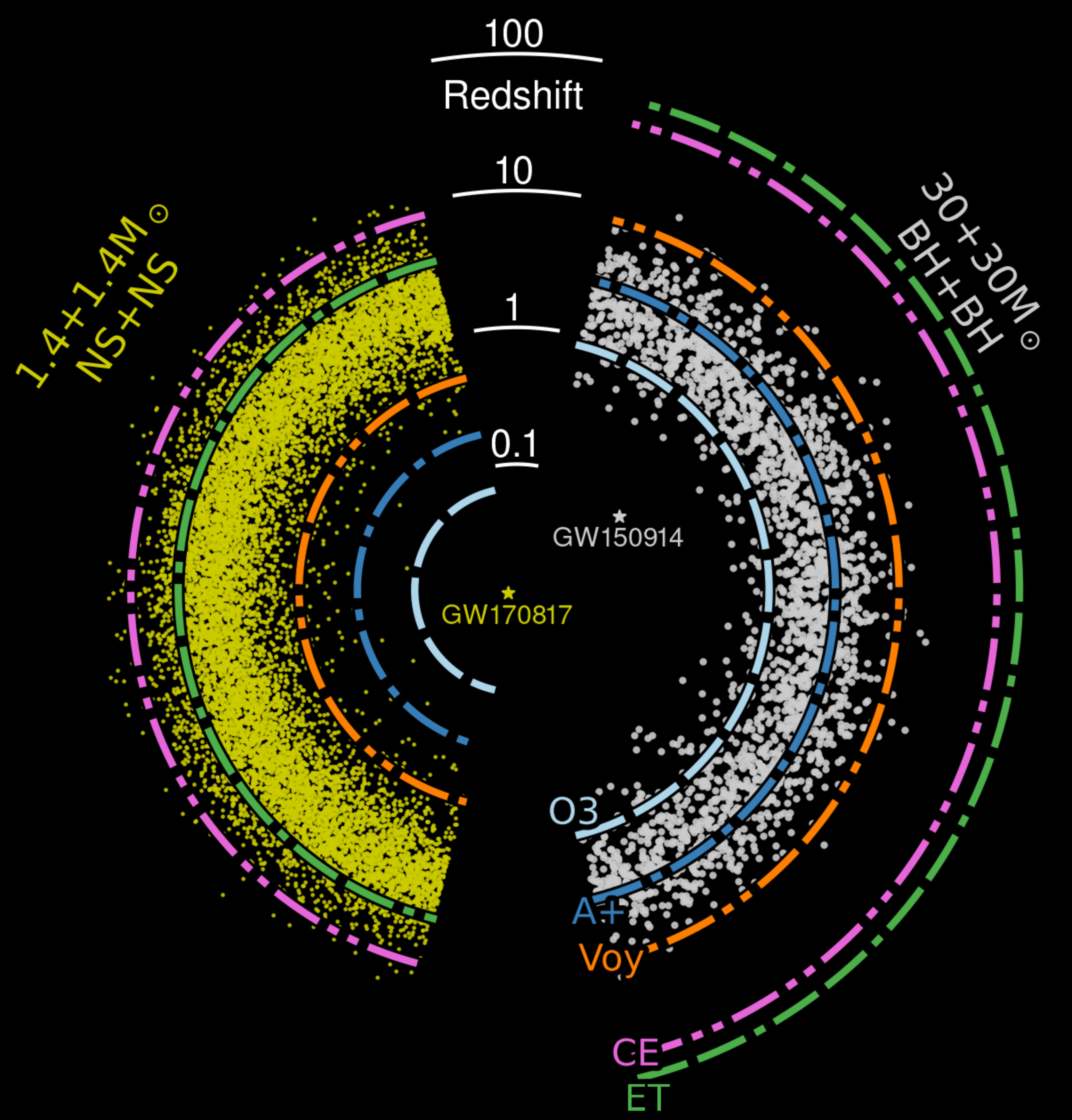

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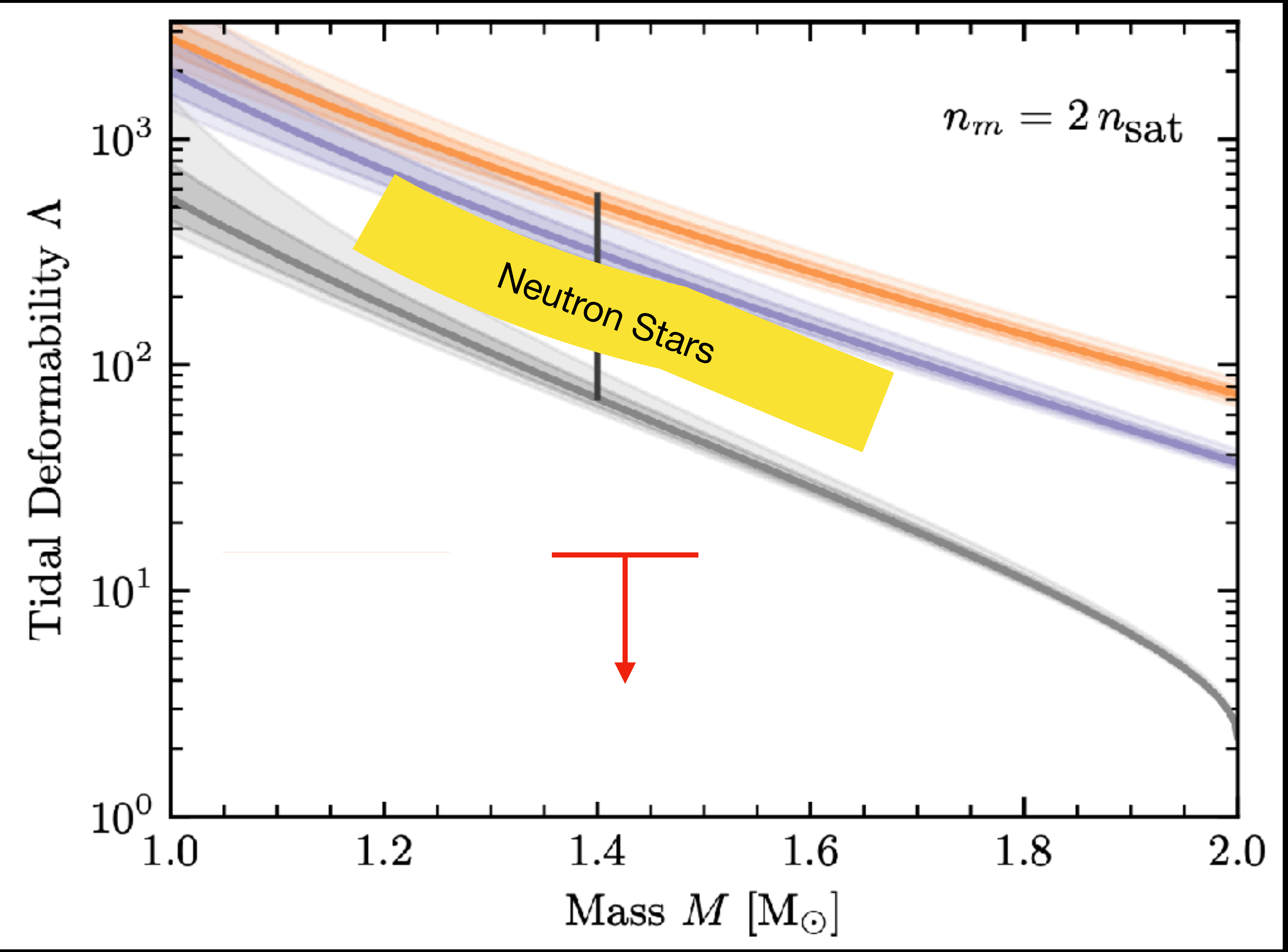

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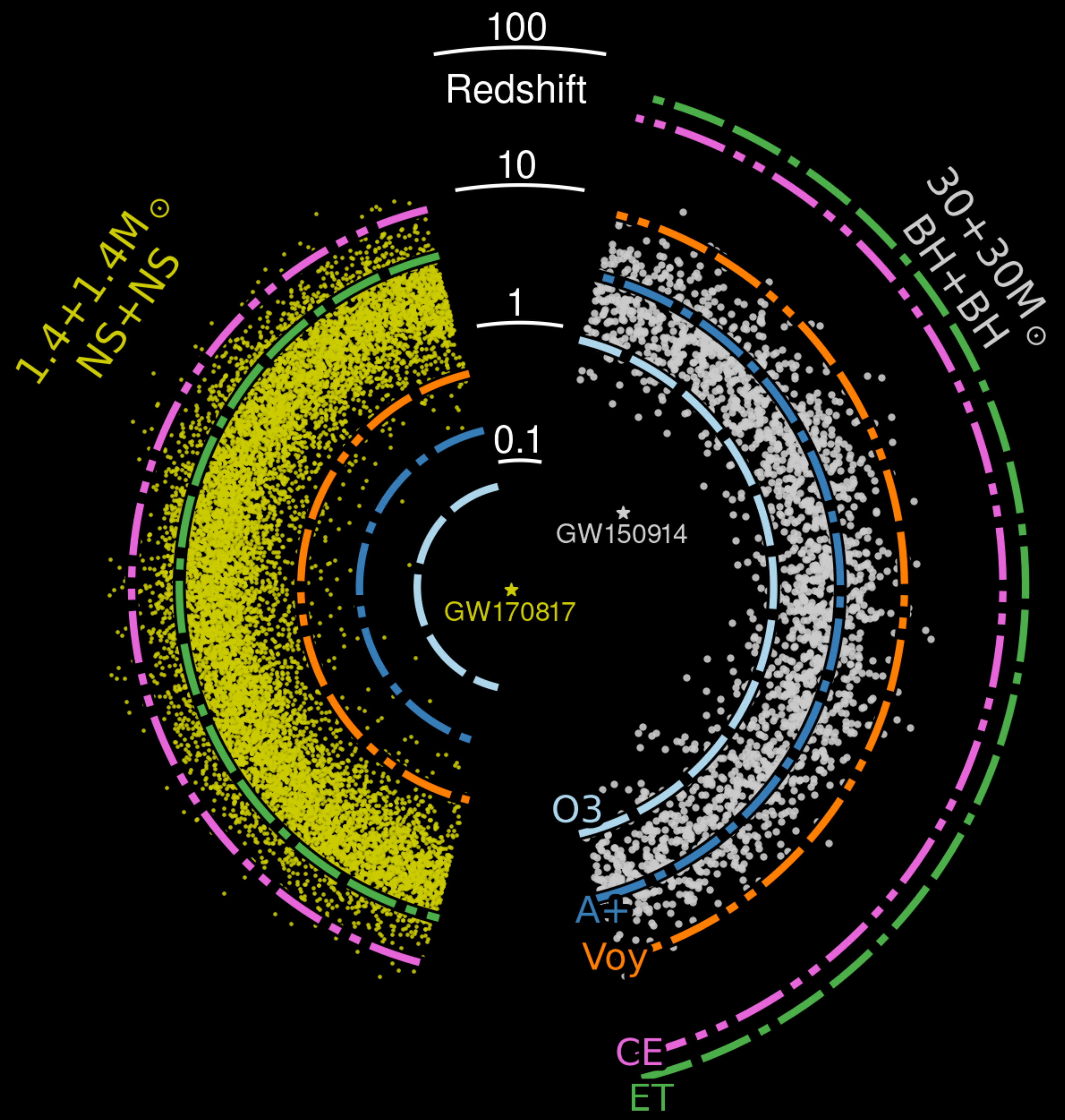

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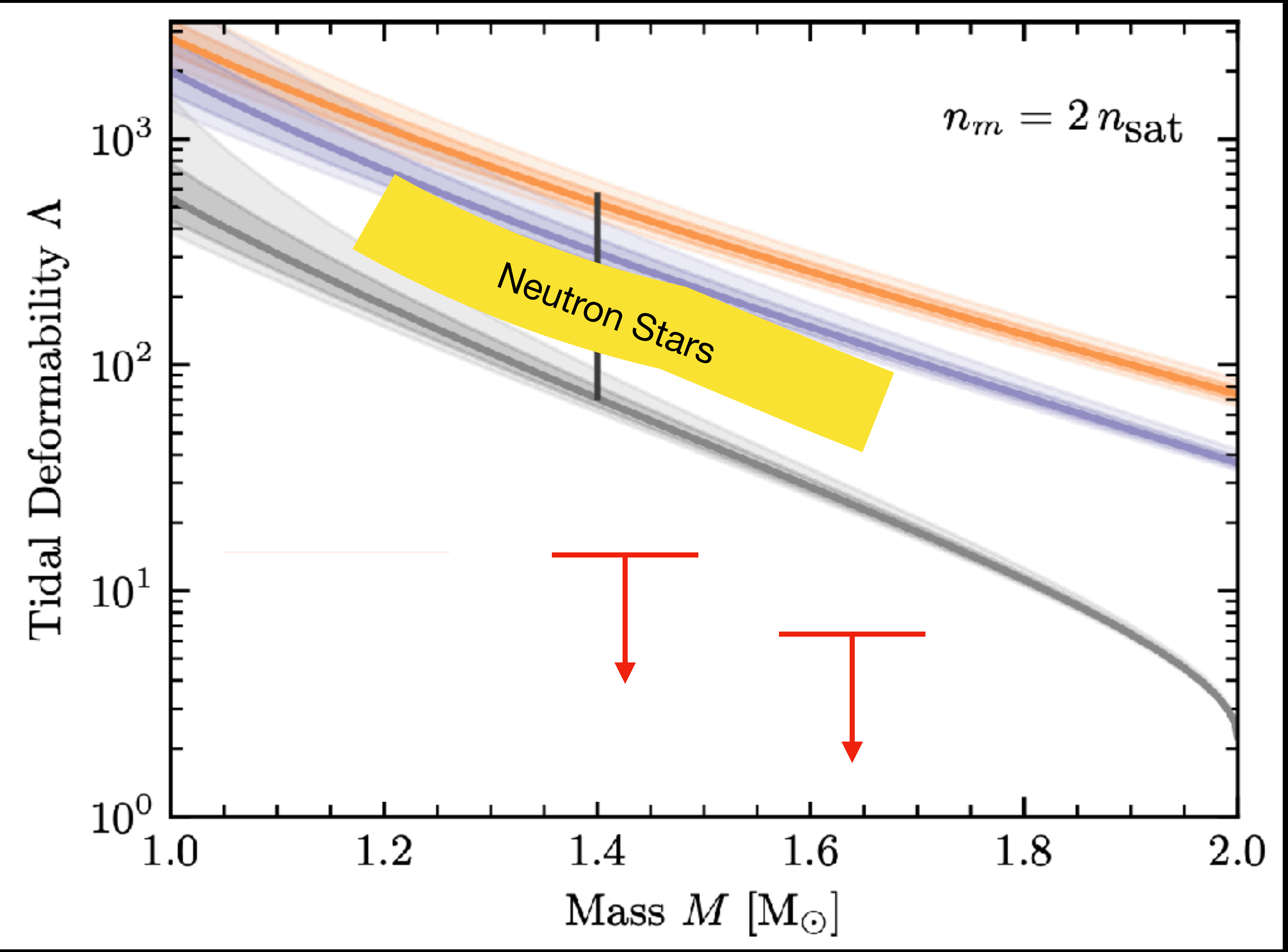

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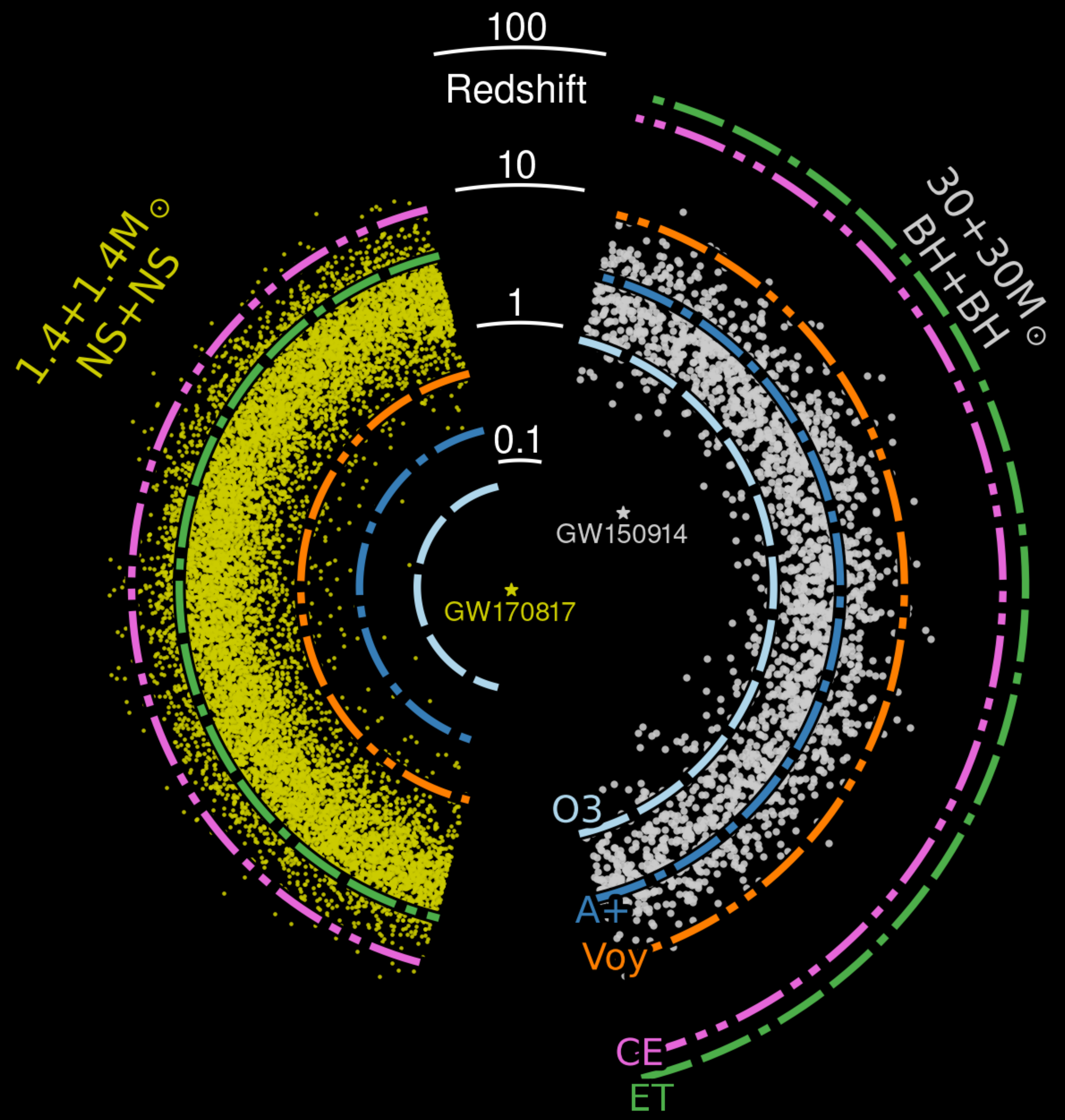

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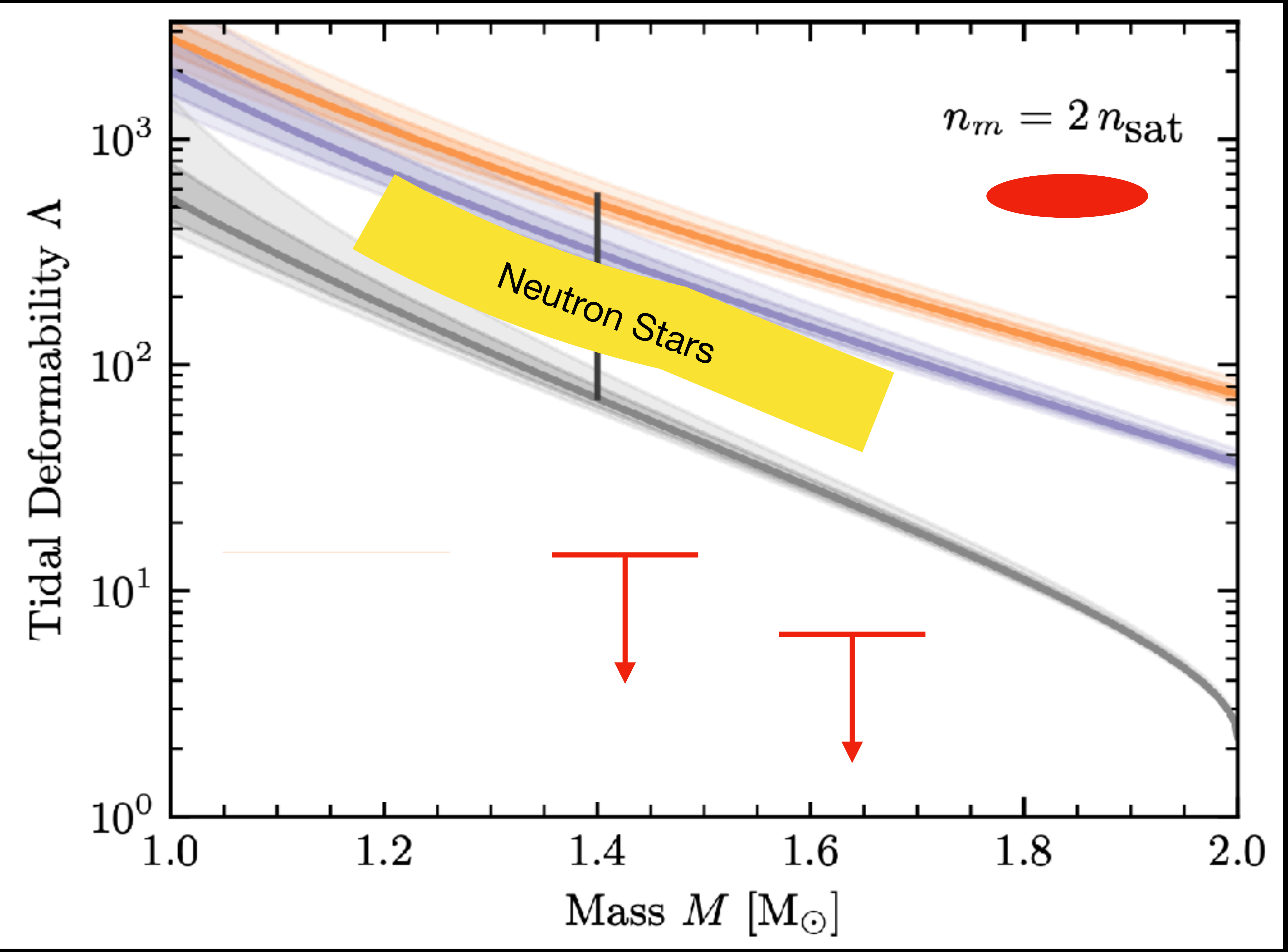

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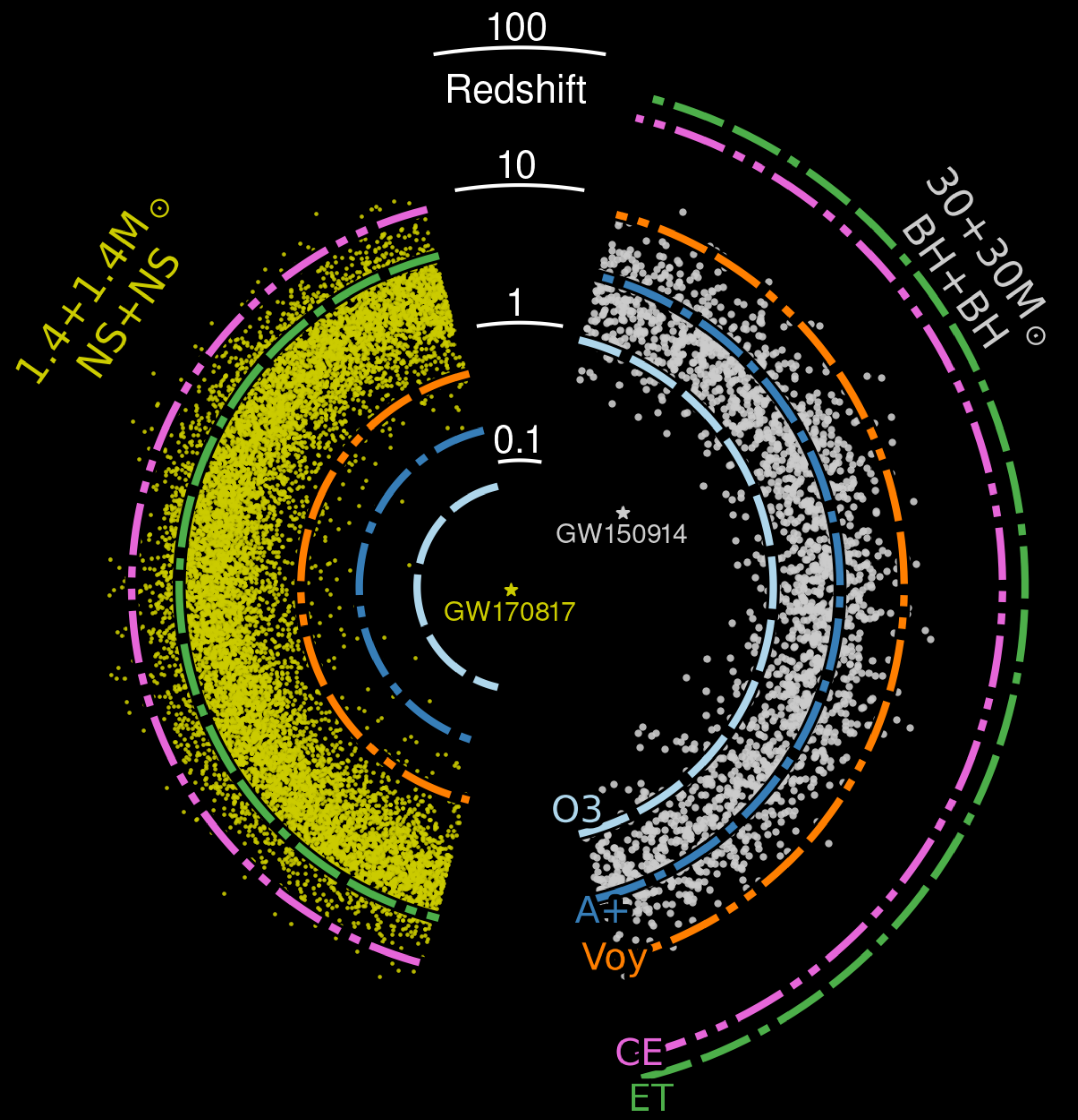

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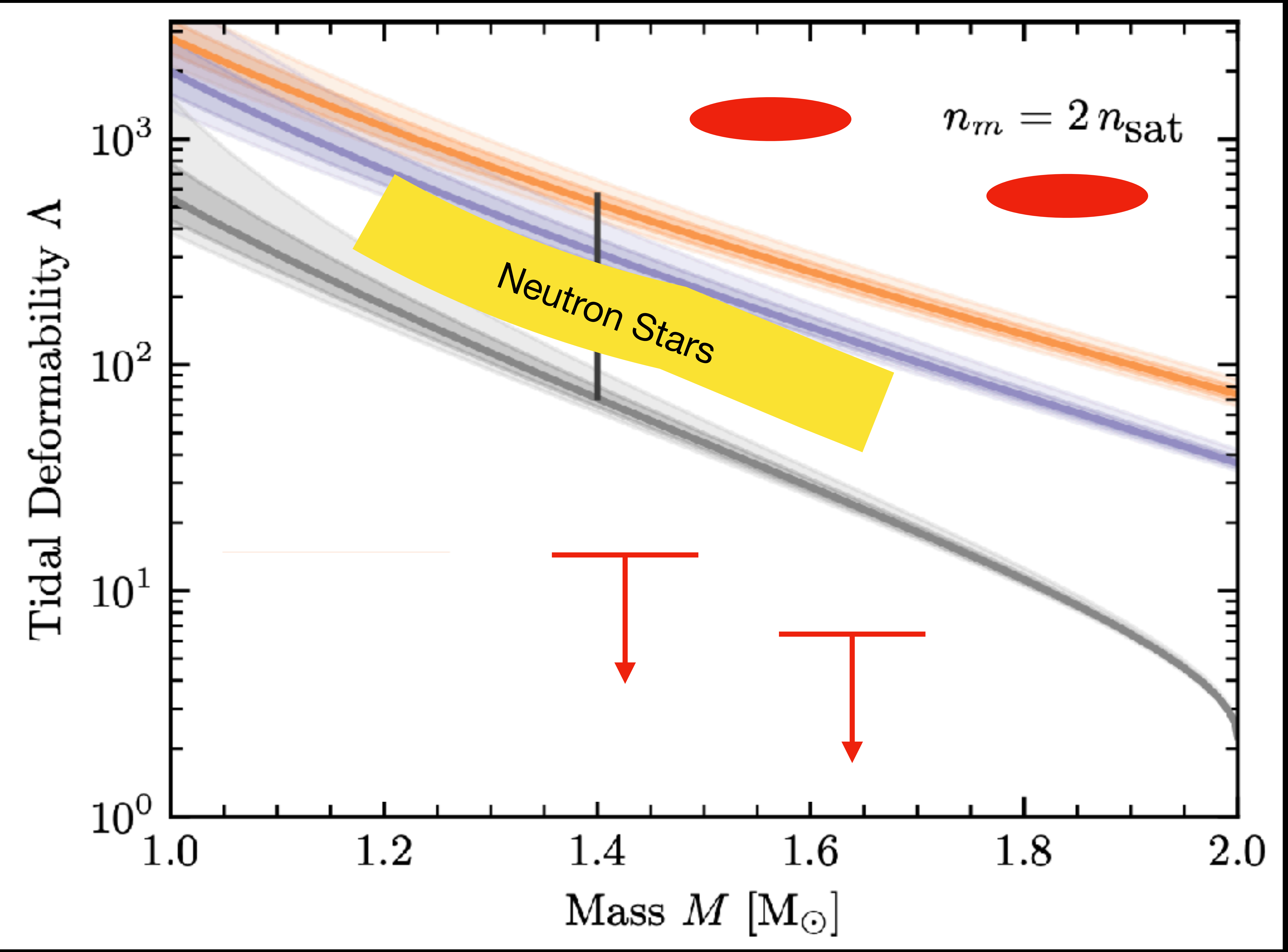

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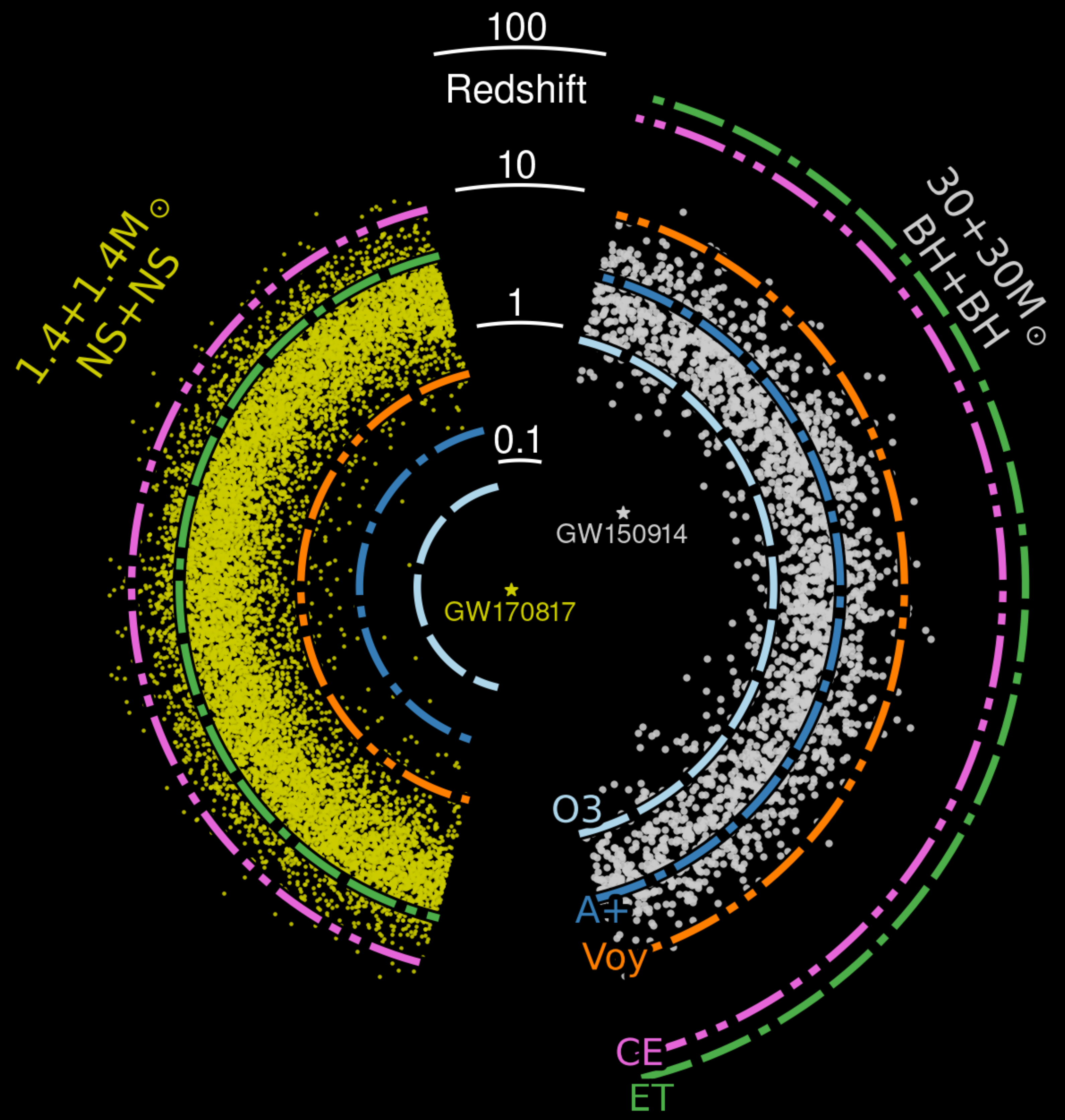

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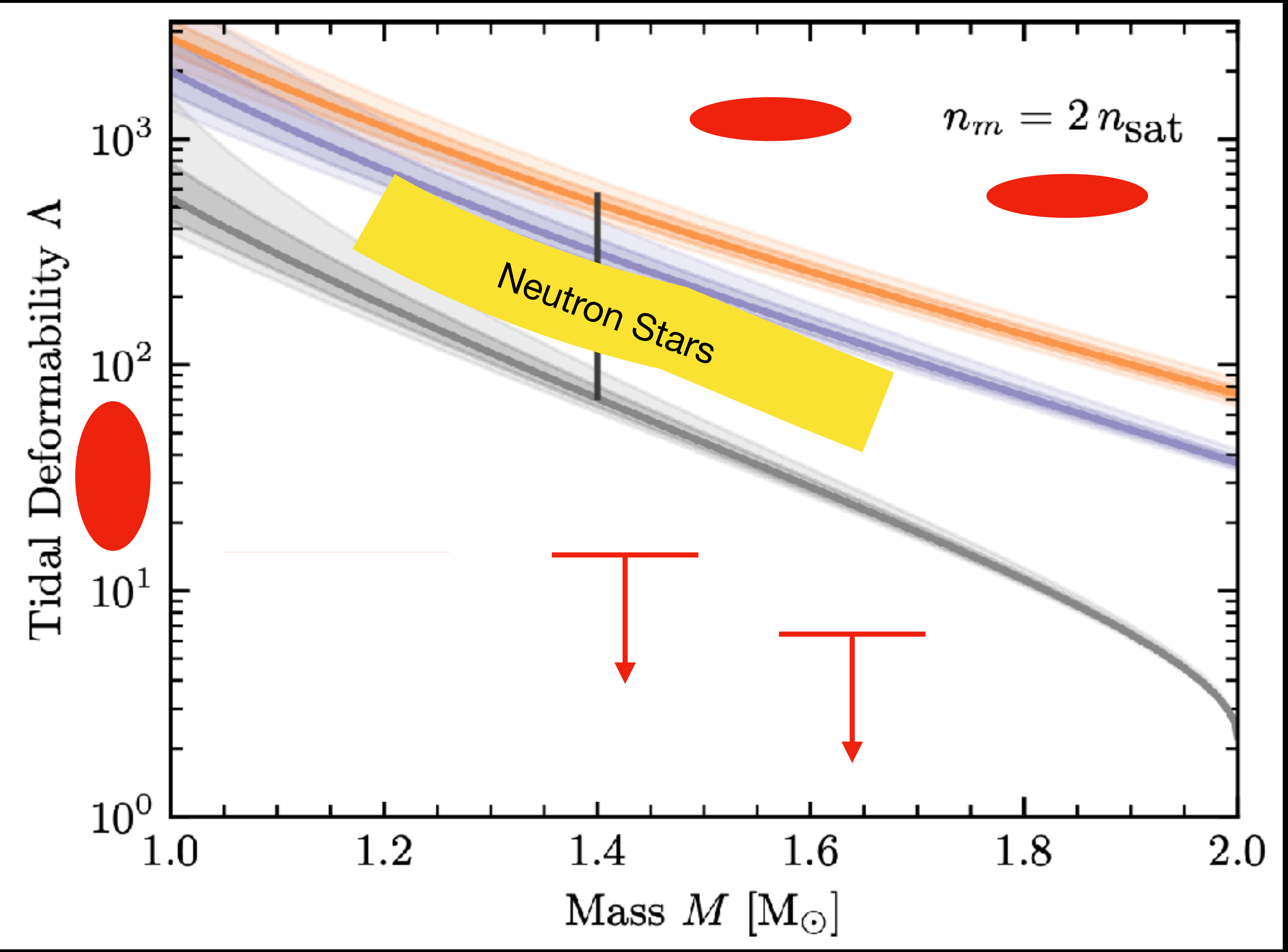

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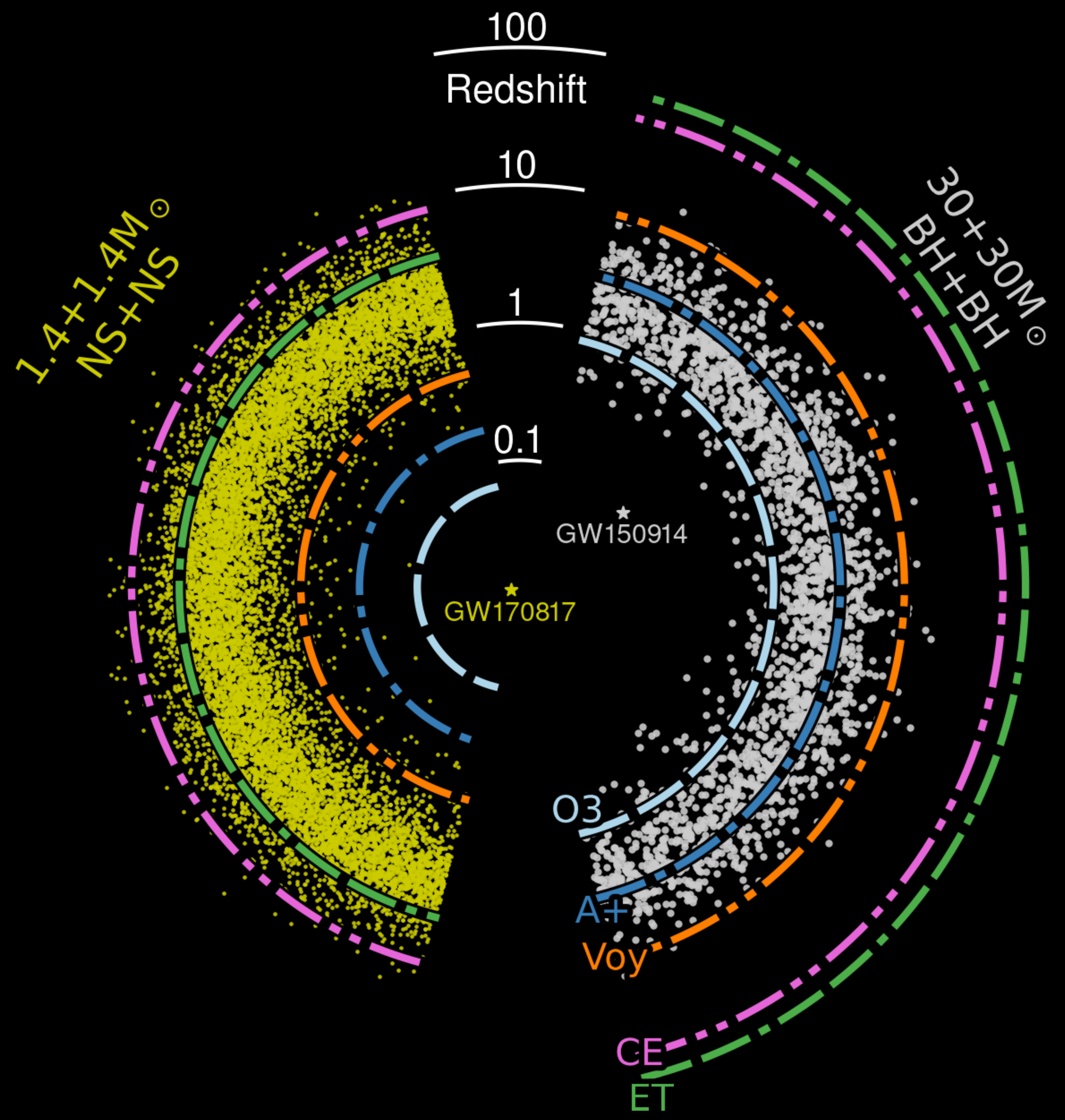

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The Dark Side of Neuton stars

Neutron stars are great places to look for dark matter:

- They accrete and trap dark matter.

$$M_\chi < 10^{-14} M_\odot \left(\frac{\rho_\chi}{1\ \mathrm{GeV/cm^3}} \right) \frac{t}{\mathrm{Gyr}}$$

- Produce dark matter due to its high density.

$$M_\chi \lesssim M_\odot \text{ for } m_\chi < 2\ \mathrm{GeV}$$

- Produce dark matter due to high temperatures at birth or during mergers.

$$M_\chi \lesssim 10^{-1}\ M_\odot \text{ for } m_\chi < 500\ \mathrm{MeV}$$

Black-Holes in the Neutron Star Mass-Range

Idea: Accretion of asymmetric bosonic dark matter can induce the collapse of an NS to a BH.

Goldman & Nussinov (1989)

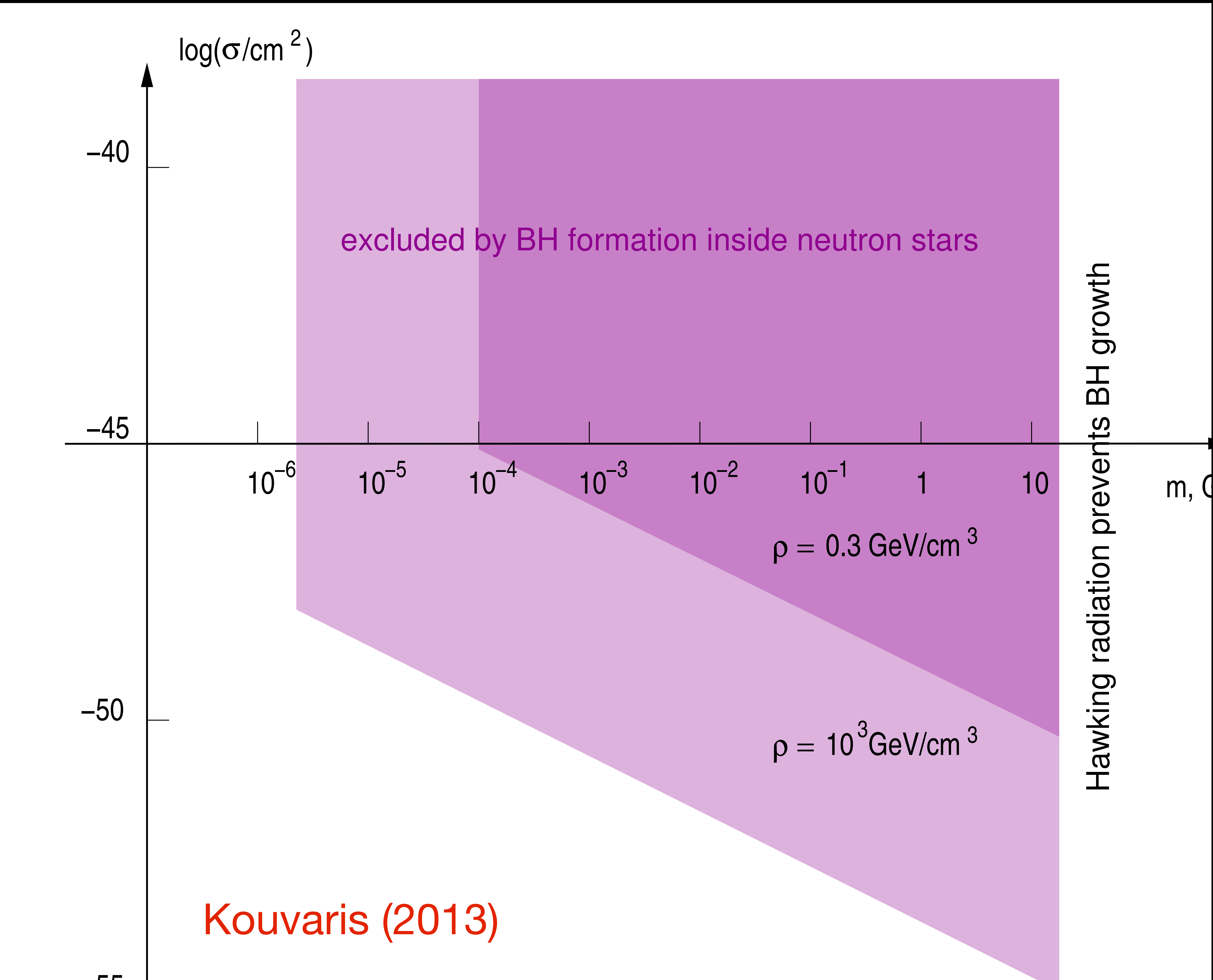
$$M_\chi \approx 10^{-14} M_\odot \ \mathrm{Min}\left[\frac{\sigma}{2\times 10^{-45}\mathrm{cm}^2}, 1\right]\left(\frac{\rho_\chi}{1\ \mathrm{GeV/cm}^3}\right)\frac{t}{\mathrm{Gyr}}$$

The maximum mass of weakly Interacting bosons is negligible:

$$M_{\mathrm{Bosons}} \approx 10^{-18}\ M_\odot \left(\frac{\mathrm{GeV}}{m_\chi}\right)$$

The existence of old neutron stars in the Milkyway with estimated ages ~ 10^{10} years provides strong constraints on asymmetric DM.

For a concise reviews see Kouvaris (2013) and Zurek (2013)

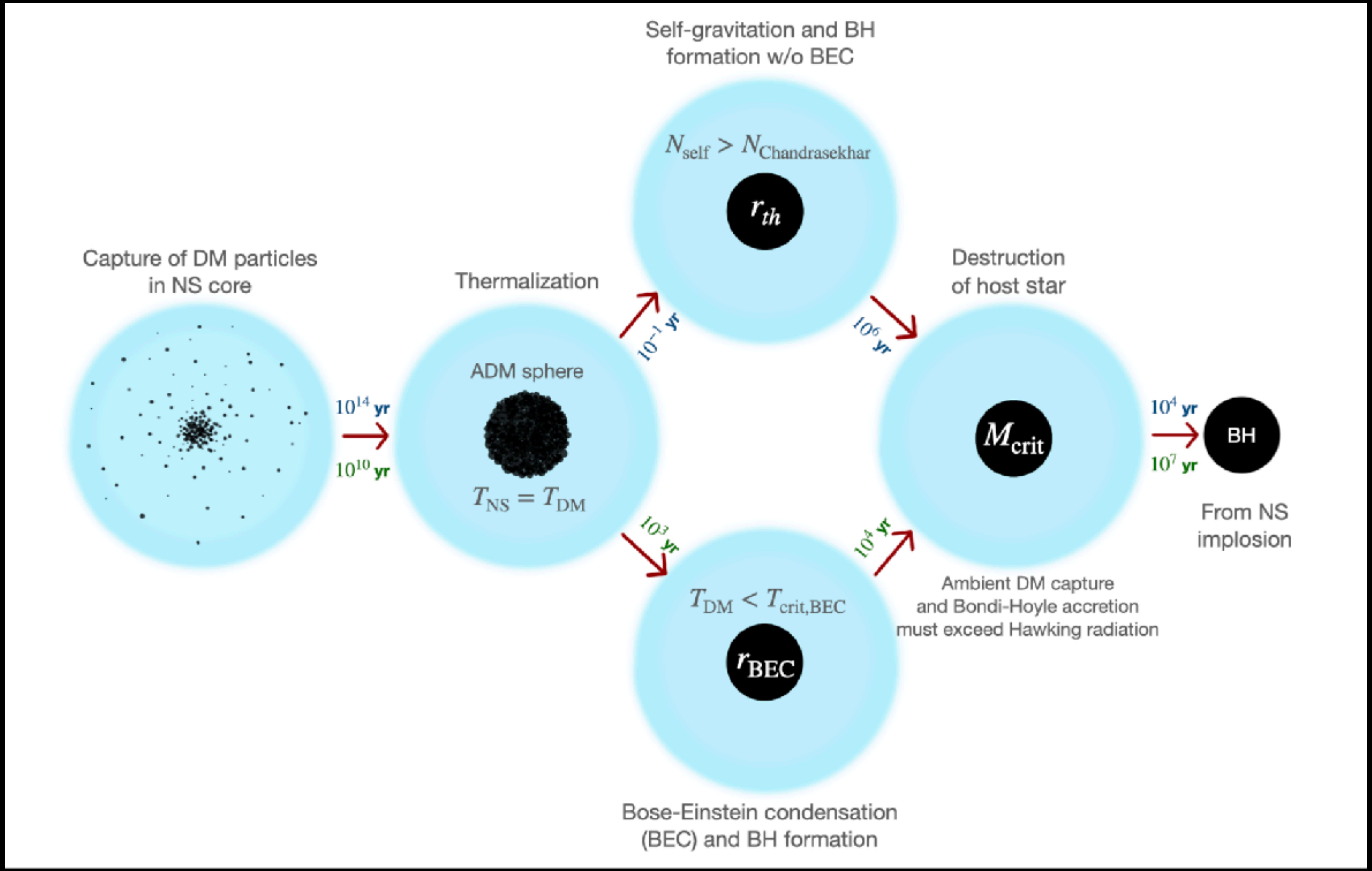


Converting NSs into BHs

For dark matter in the 1-10^6 GeV mass range, black hole formation is complex and involves several timescales.

Capture time is typically the limiting step. But, thermalization can be slow in exotic superfluid phases and depends on processes in the inner core!

C. Kouvaris and P. Tinyakov (2011)
S. D. McDermott, H.-B. Yu, and K. M. Zurek, (2012)
B. Bertoni, A. E. Nelson, and S. Reddy (2013)
+ many more more refined recent analysis.



Divya Singh, Gupta, Berti, Reddy, Sathyaprakash (2023)

Baryon Number Violation in Neutron Stars

Particles in the MeV-GeV mass range that mix with baryons very weakly are natural dark matter candidates.

There was speculation that a dark baryon with mass m_χ between 937.76 - 938.78 MeV might explain the neutron life-time discrepancy:

$$n \rightarrow \chi + \ldots$$

Fornal & Grinstein (2018)

$\tau_n^{\rm bottle} = 879.6 \pm 0.6 \ {\rm s}$ —— counts neutrons

$\tau_n^{\rm beam} = 888.0 \pm 2.0 \ {\rm s}$ —— counts protons

$$\mathrm{Br}_{n\rightarrow\chi} = 1 - \frac{\tau_n^{\rm bottle}}{\tau_n^{\rm beam}} = (0.9 \pm 0.2) \times 10^{-2}$$

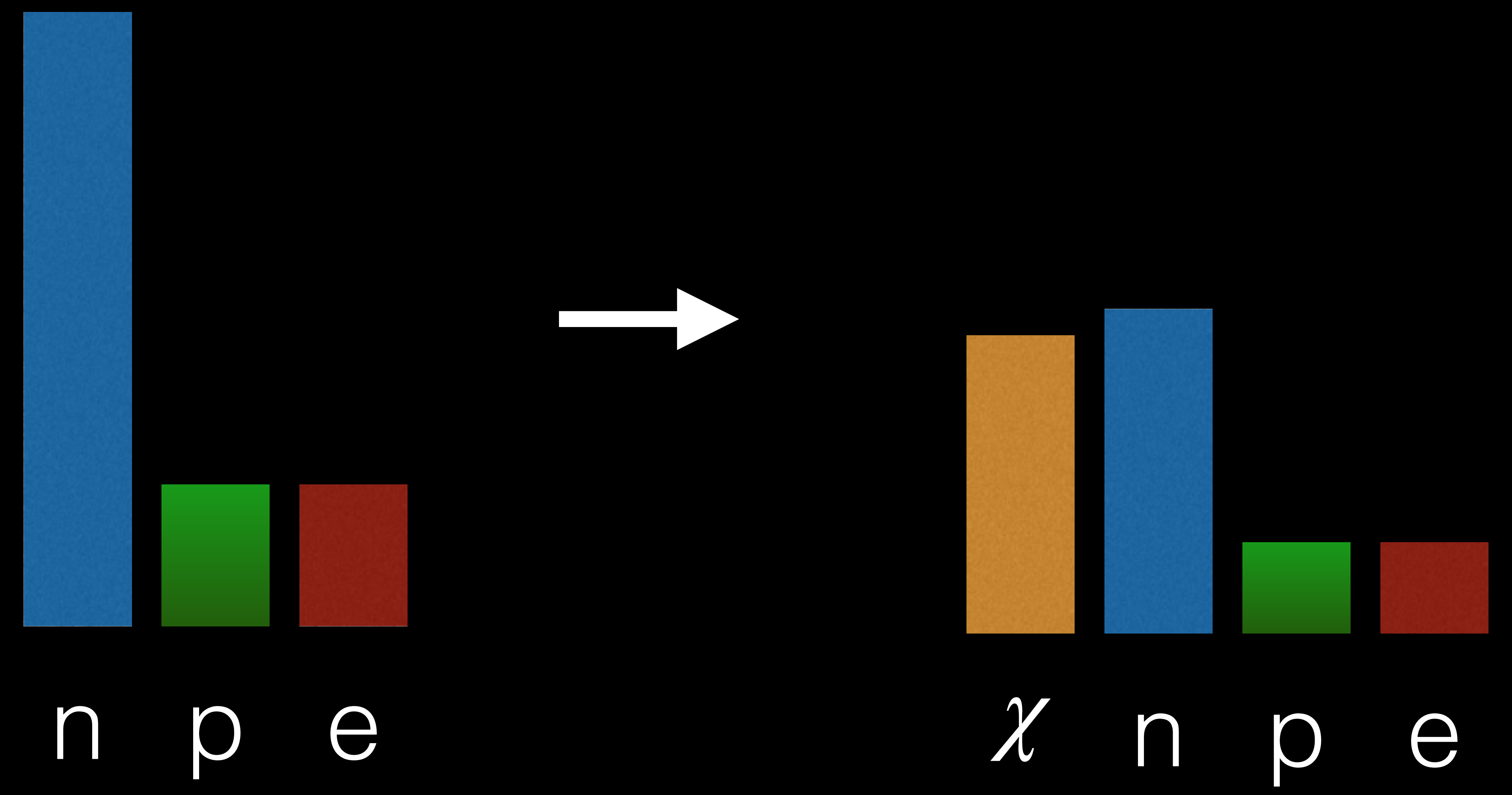
A model for hidden baryons which mix with the neutron:

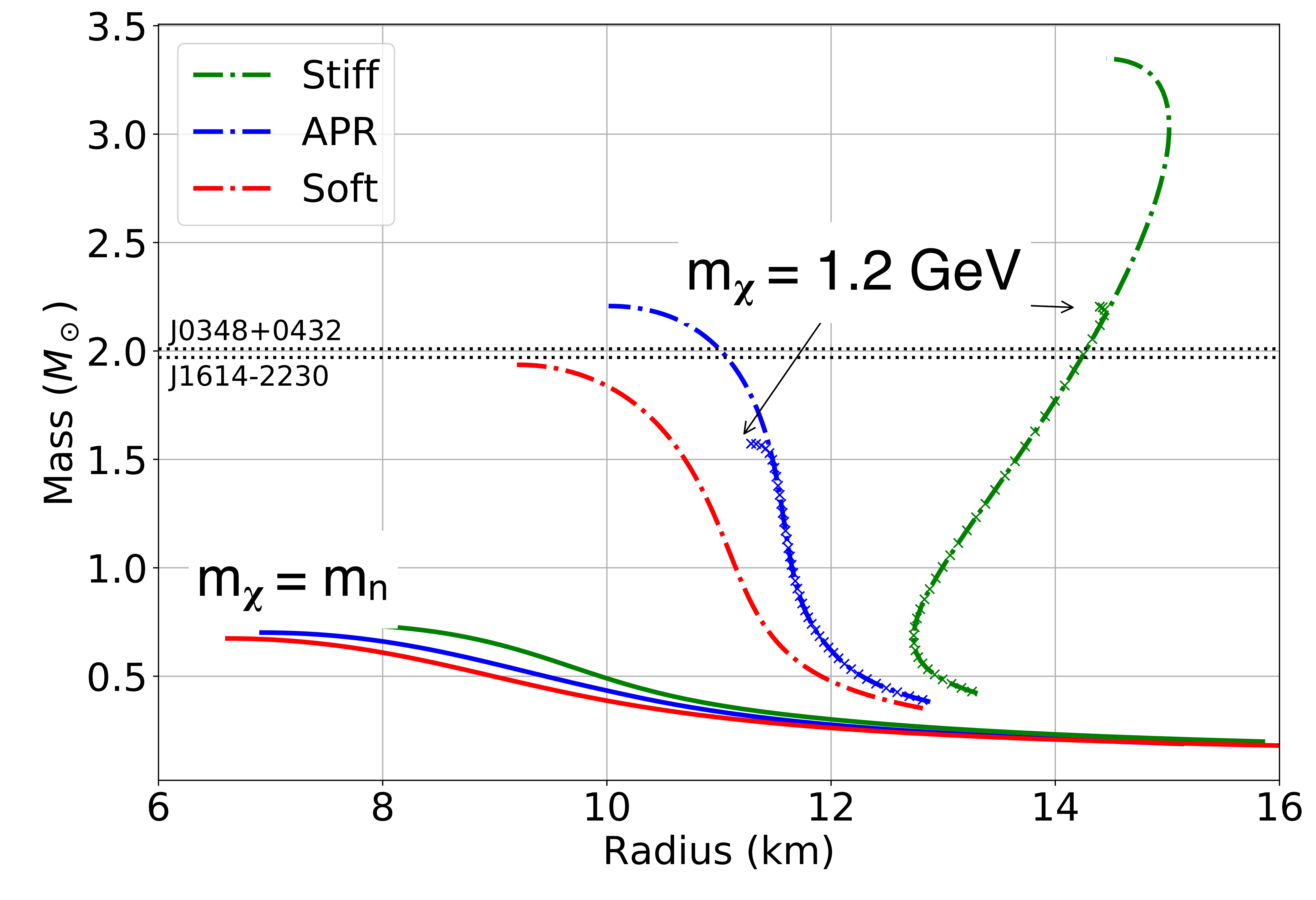
$$\mathcal{L}_{\rm eff} = \bar{n}\,(i\partial\!\!\!/ - m_n)\,n + \bar{\chi}\,(i\partial\!\!\!/ - m_\chi)\,\chi - \delta\,(\bar{\chi}n + \bar{n}\chi)$$

Mixing angle: $\theta = \dfrac{\delta}{\Delta M}$ ⇒ An explanation of the anomaly requires $\theta \simeq 10^{-9}$

Neutron stars can probe smaller mixing angles $\theta \simeq 10^{-18}$ and masses up to 2 GeV.

Weakly Interacting Dark Baryons Destabilize Neutron Stars





Neutron decay lowers the nucleon density at a given energy density.

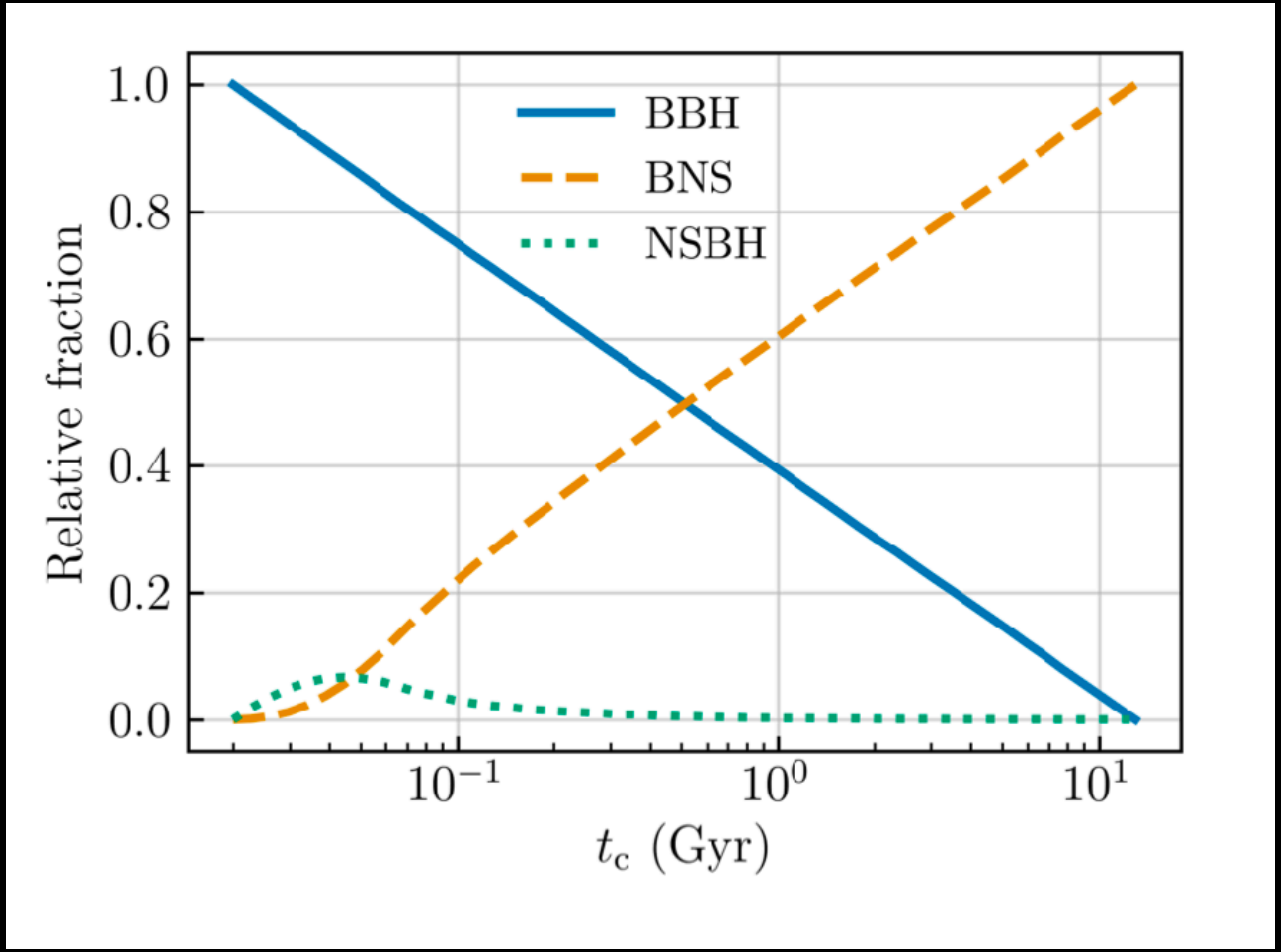
When dark baryons are weakly interacting the maximum mass of neutron stars is greatly reduced.

Observed neutron stars exclude dark baryons with mass < 1.2 GeV.

Mckeen, Nelson, Reddy, Zhou (2018) Baym, Beck, Geltenbort, Shelton (2018) Motto, Guichon, Thomas (2018)

Inferring Conversion Timescales from Future GW Observations

- Measuring many binary masses and tidal deformability presents unique opportunities beyond discovering BHs in the NS mass range.
- The conversion timescale can be inferred if it is comparable to the binary coalescence time scale (delay timescale) from the fraction of BBH in the NS mass-range.
- In simple scenarios, the conversion timescale can be inferred quite accurately with next-generation detectors.



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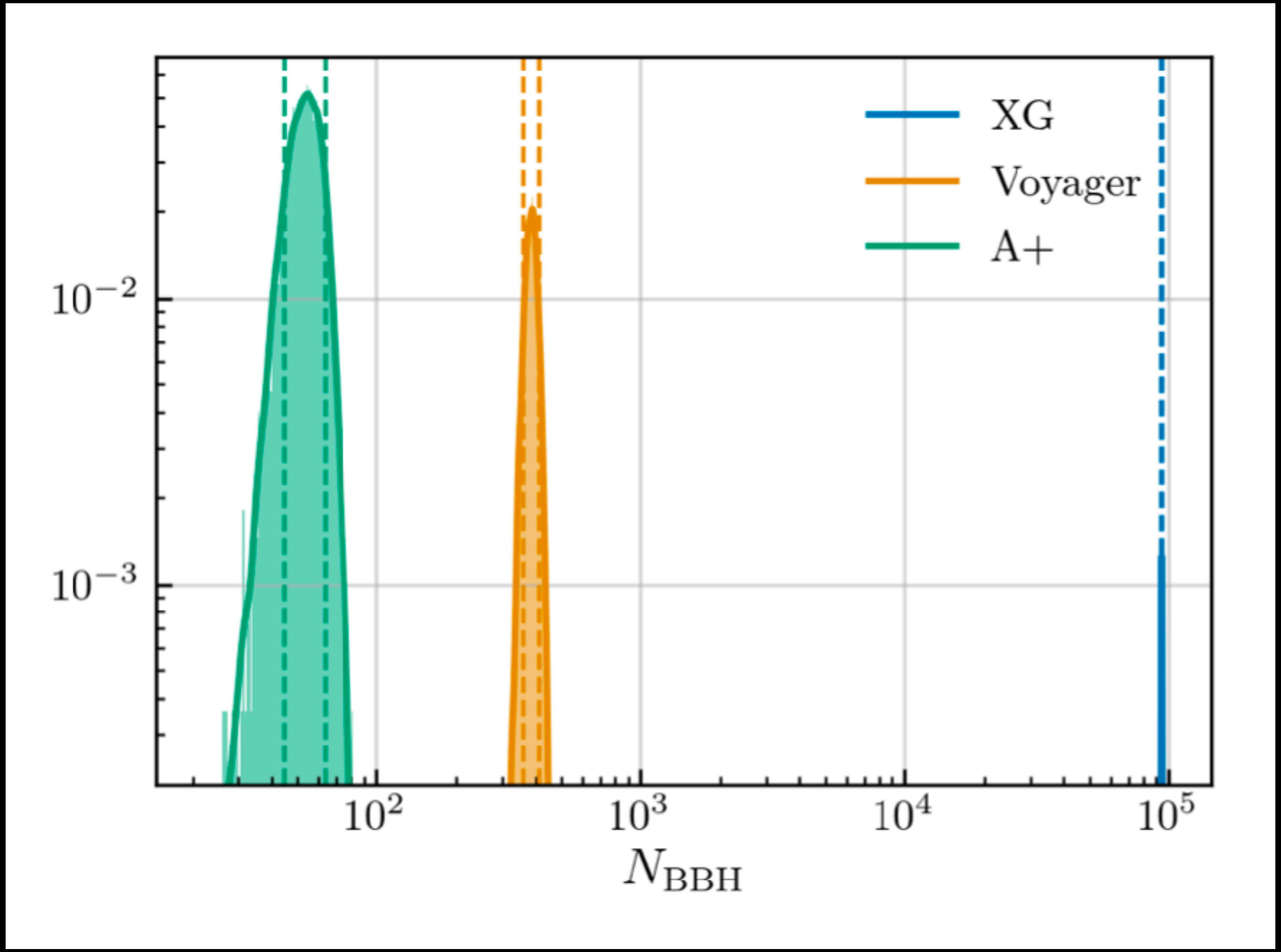

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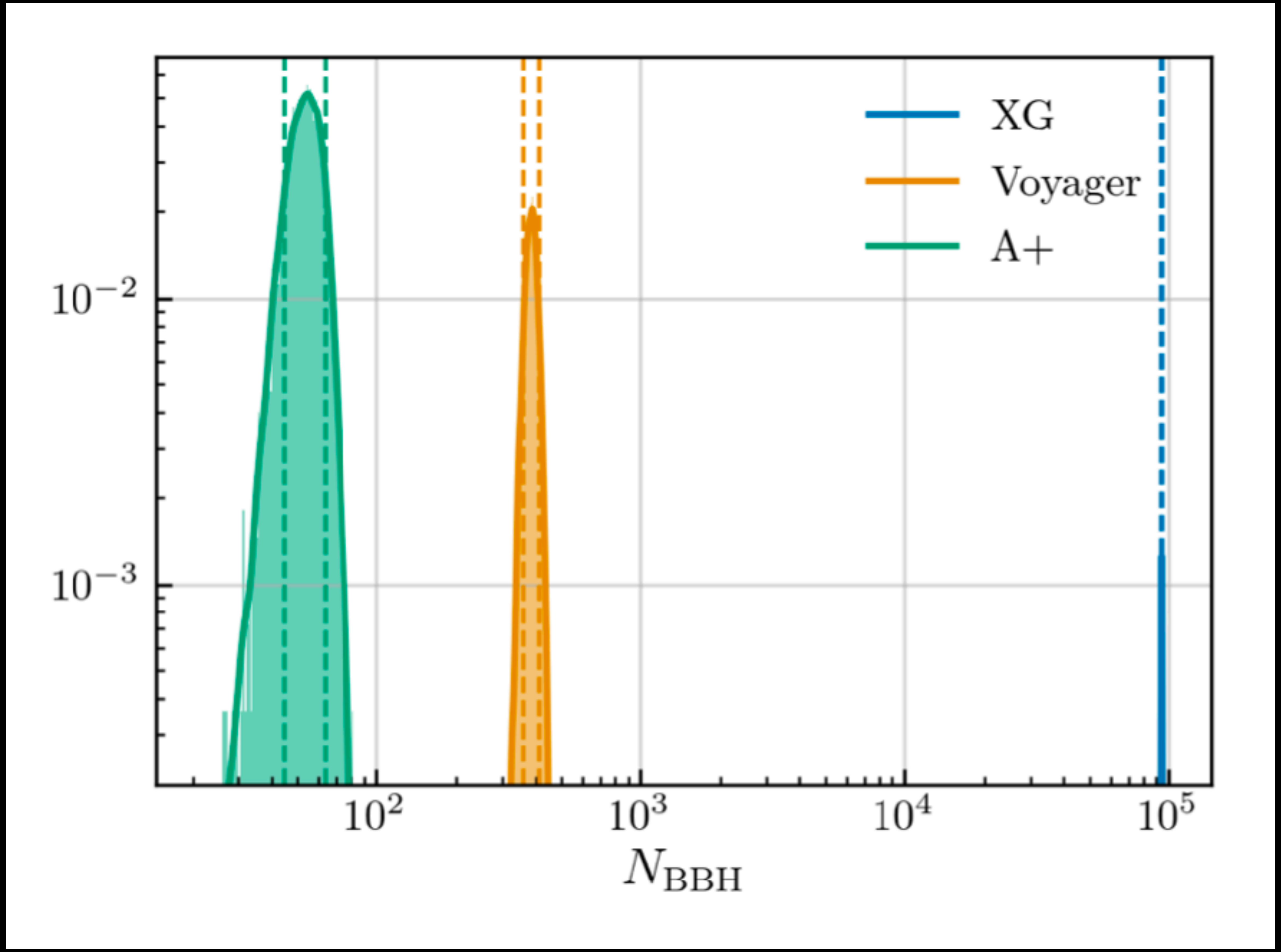

BBH and BNS distributions for a hypothetical conversion timescale of 1 Gyr.

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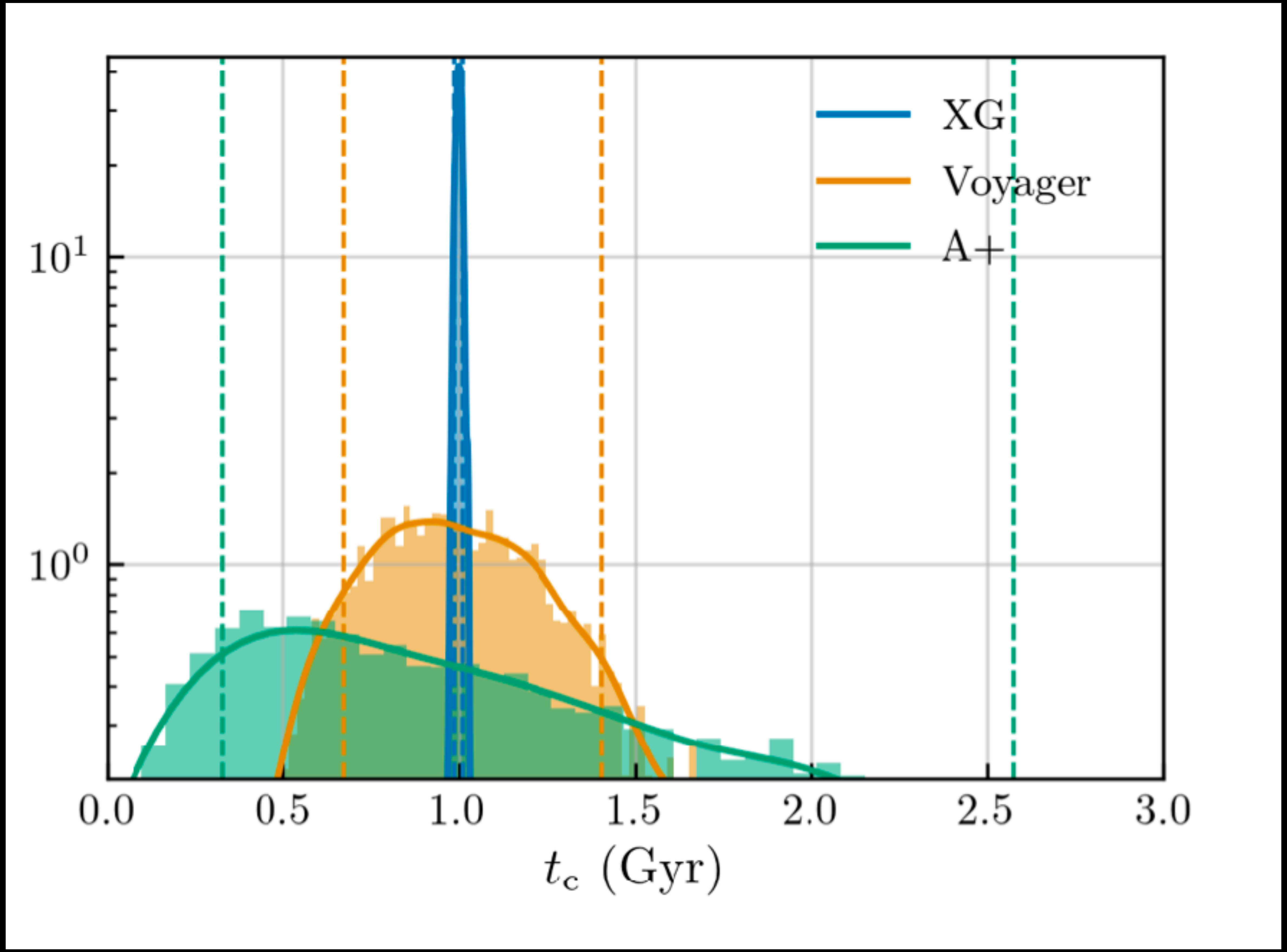

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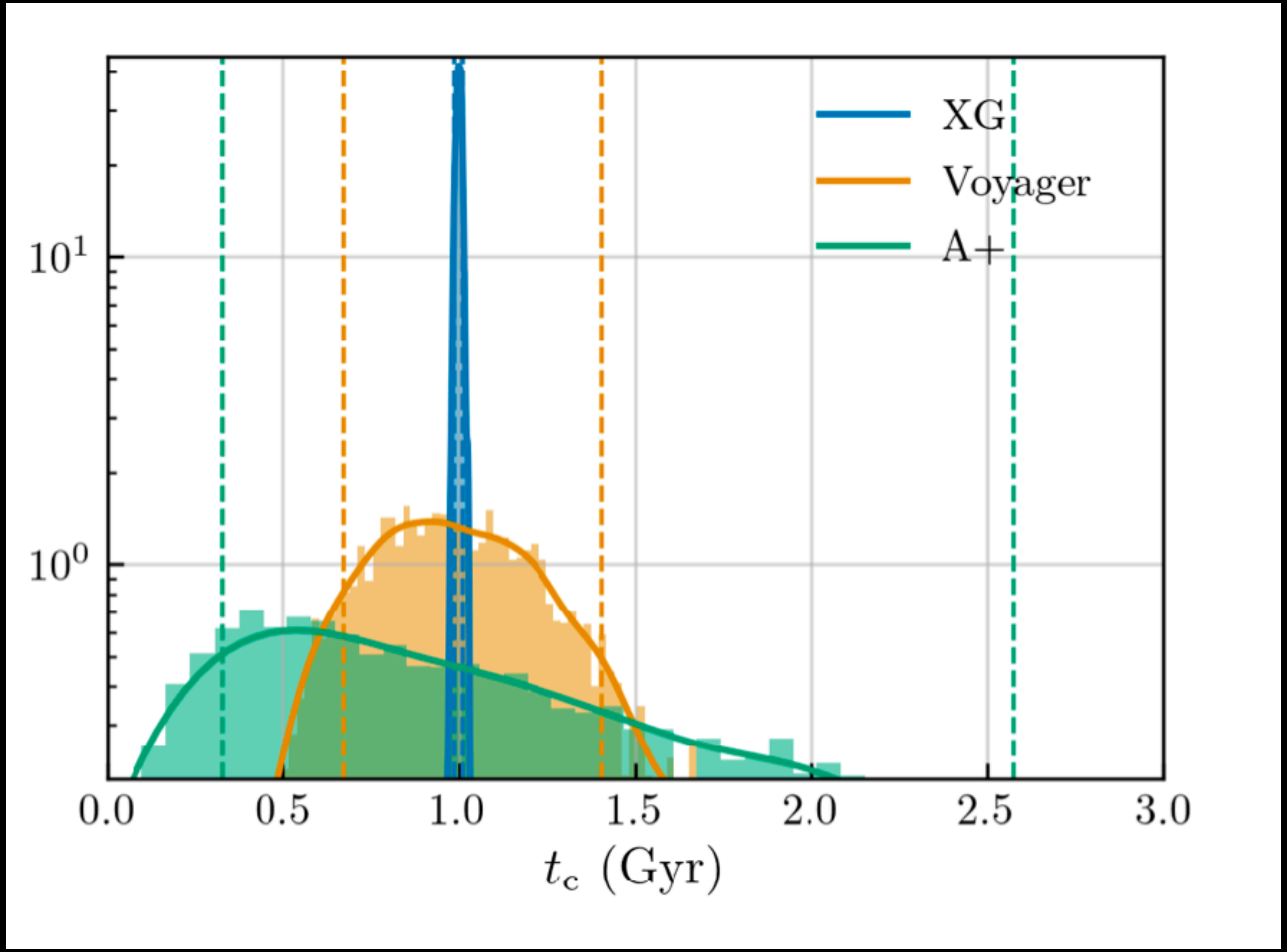
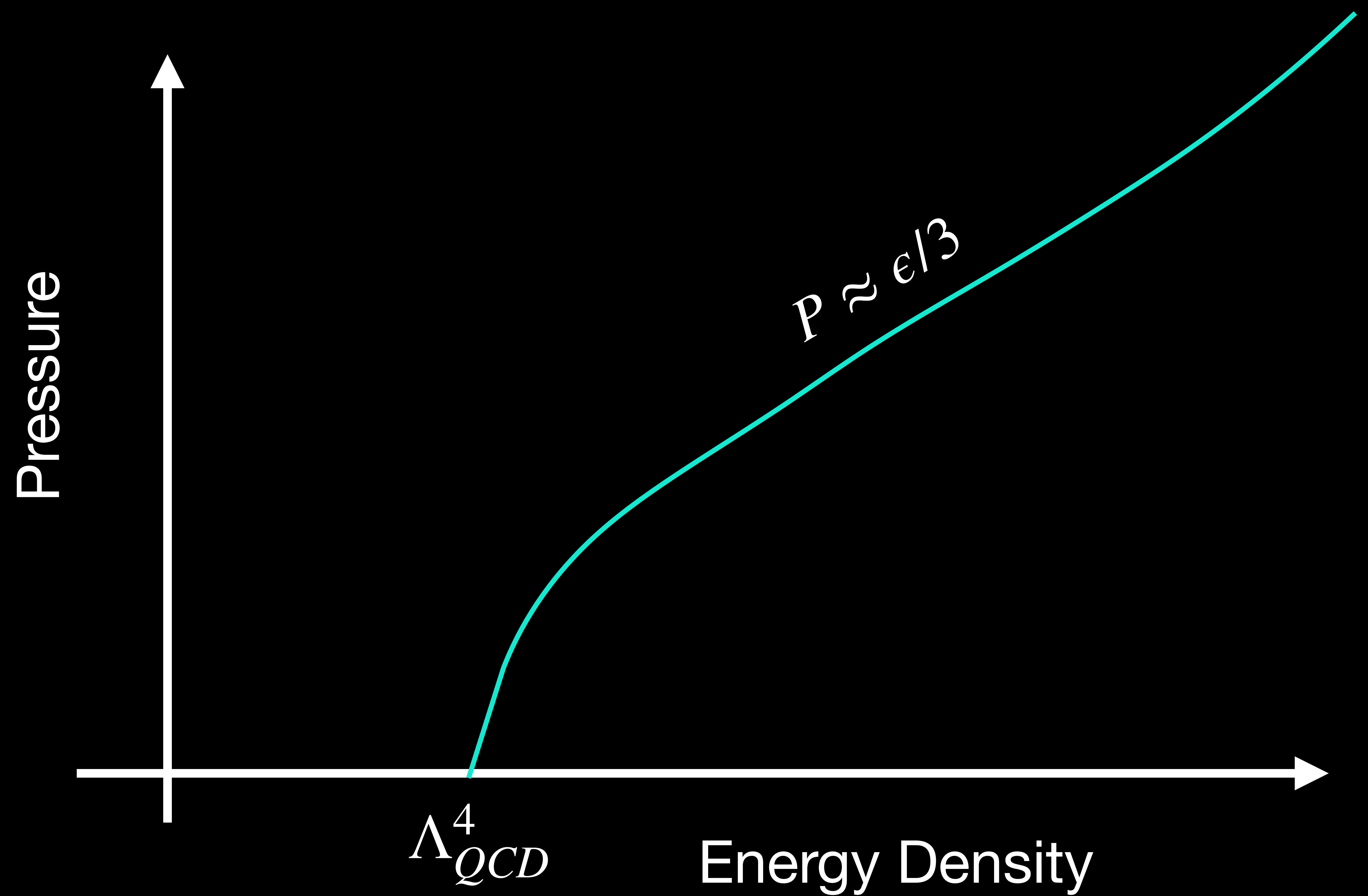
Divya Singh, Gupta, Berti, Reddy, Sathyaprakash (2023)



BBH and BNS distributions for a hypothetical conversion timescale of 1 Gyr.
Conversion timescale inferred in 5 years

QCD-like Dark Matter without Long-Range Forces.

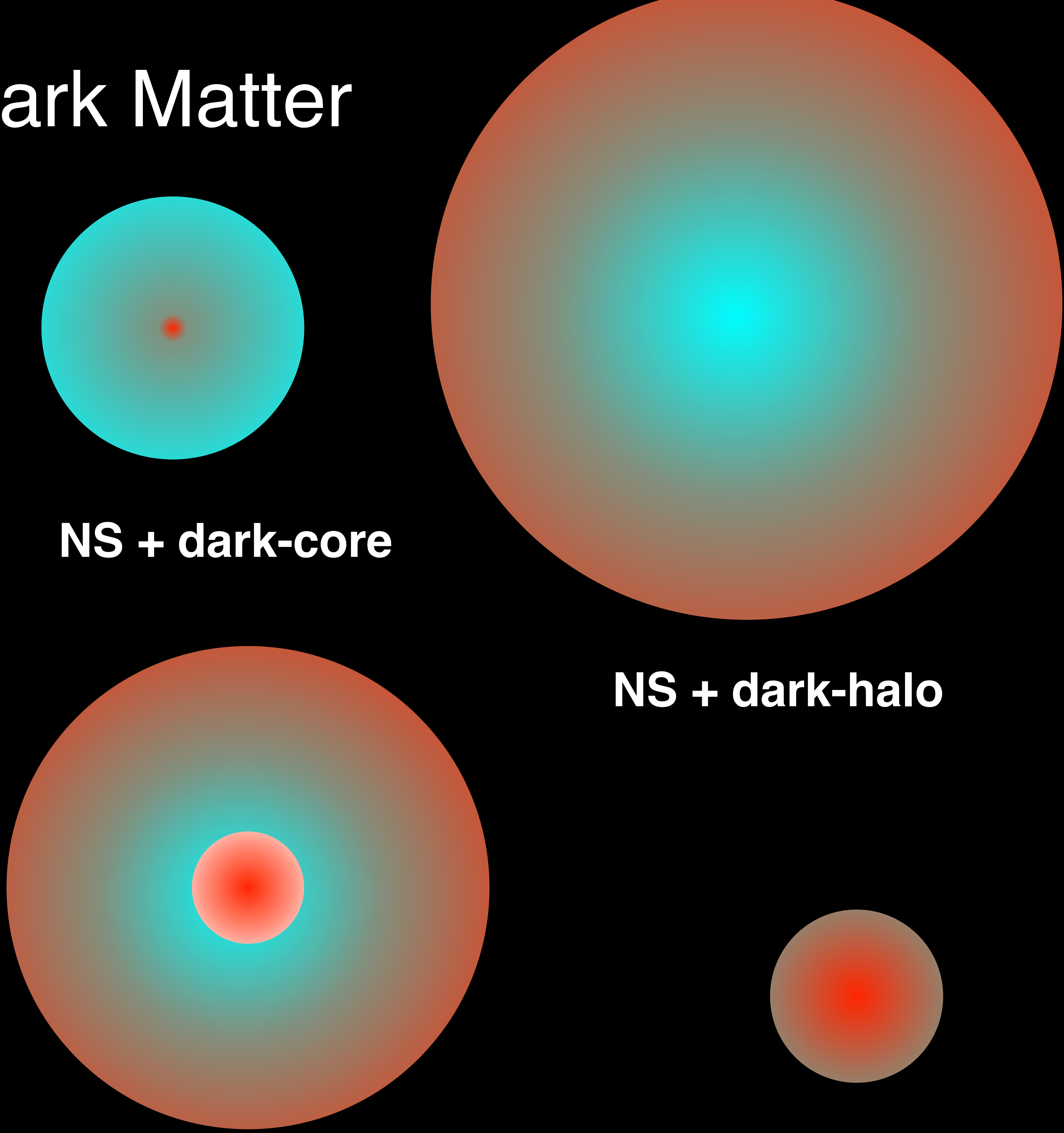


Self-interacting Dark Matter

Self-interacting dark matter could form hybrid neutron stars and compact dark objects.

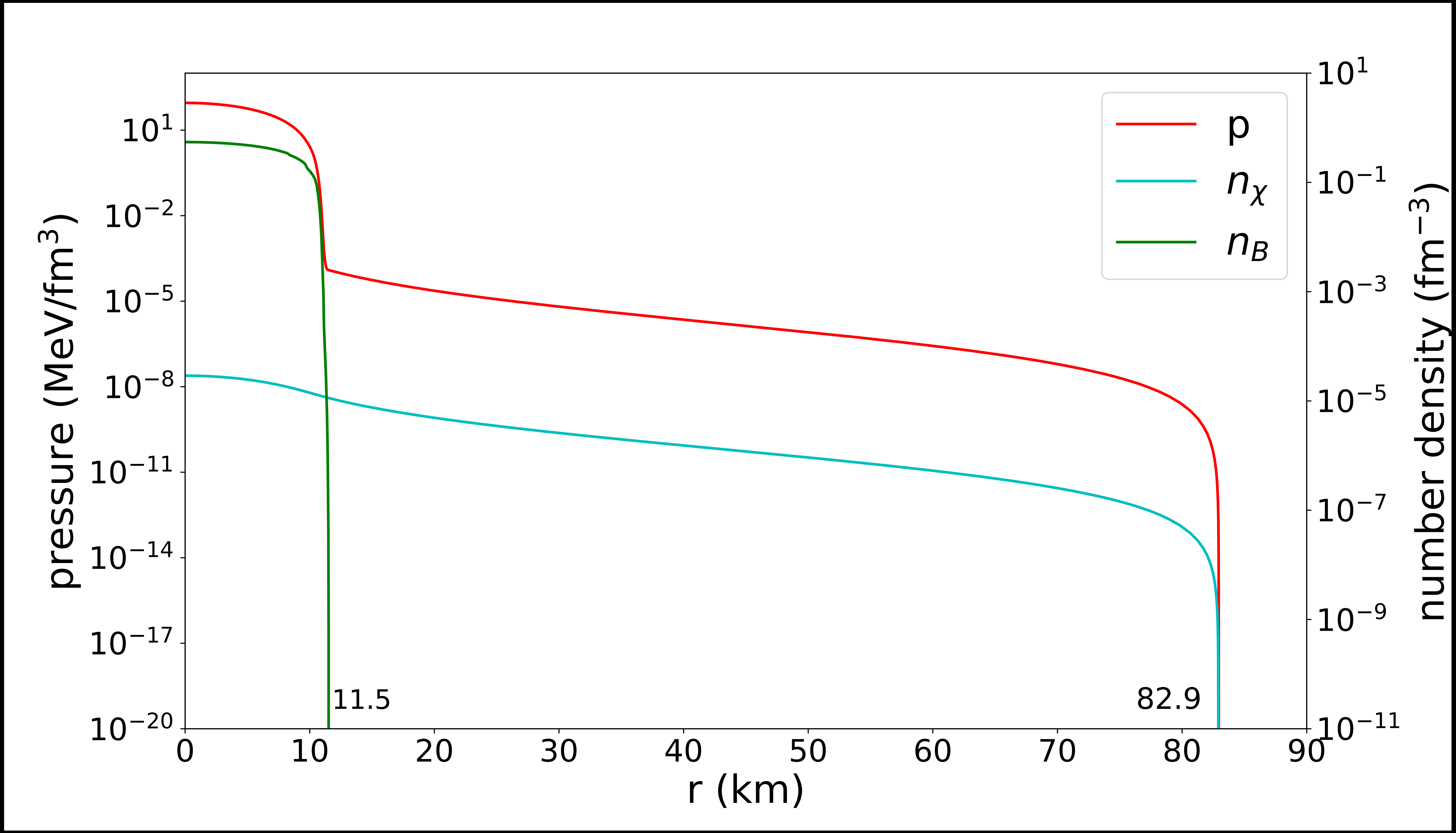
Gravitational wave observations of binary compact objects whose masses and tidal deformability's differ from those expected from neutron stars and stellar black holes would provide conclusive evidence for a strongly self-interacting dark sector:

Mass $< 0.1\ M_{solar}$
Tidal Deformability > 600



Nelson, Reddy, & Zhou (2018)   Horowitz & Reddy (2018)

Profile of a Neutron Star with a Bosonic Dark Halo



1.4 M_{solar} Neutron star with 10^{-4} M_{solar} of dark matter.

Dark matter: m_χ = 100 MeV   Interactions: g_χ/m_Φ = (0.5/MeV)

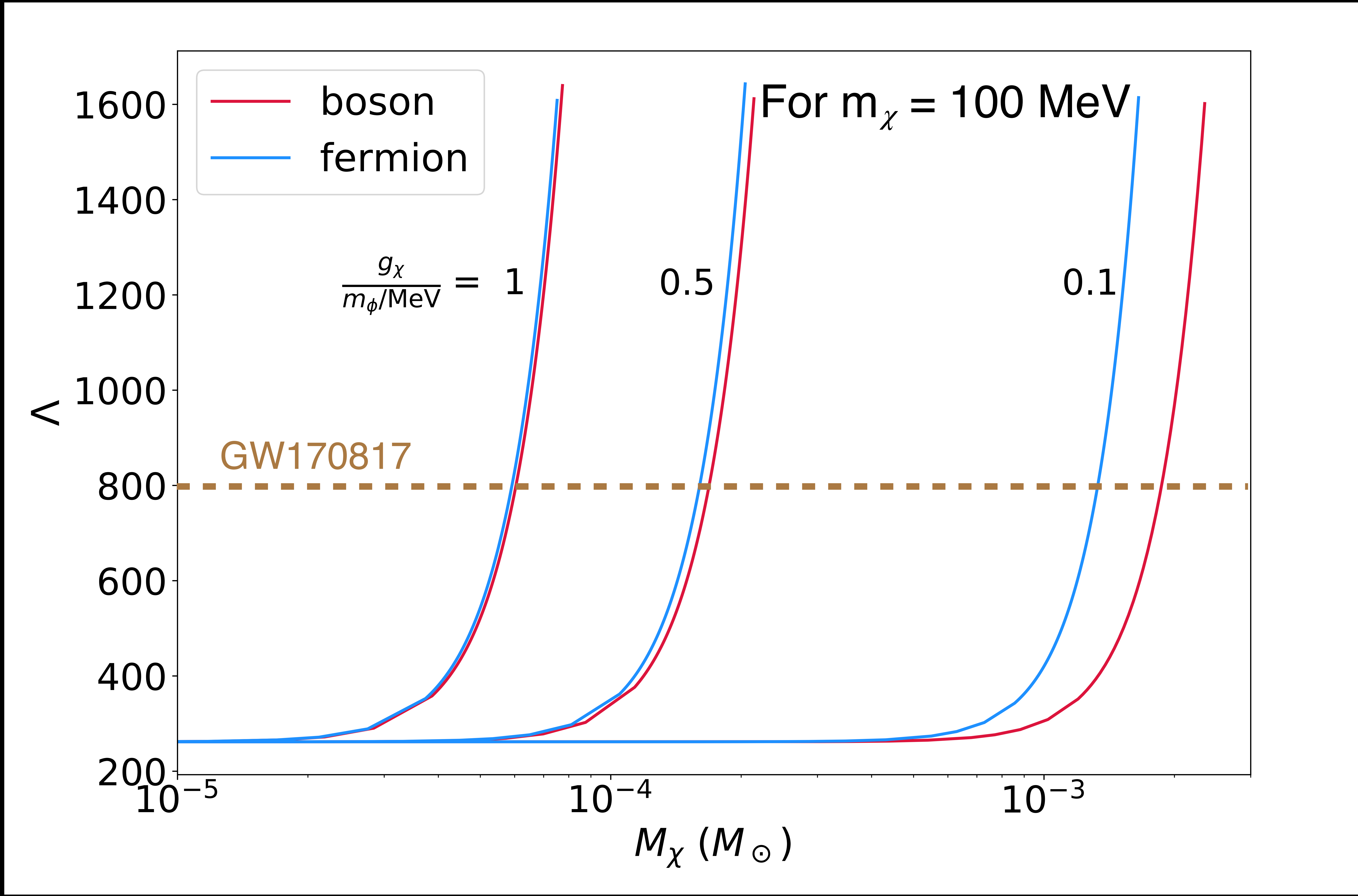
Nelson, Reddy, Zhou (2018)

Dark Halos Alter Tidal Interactions

Trace amount of light dark matter ~ 10^{-4}-10^{-2} M_{solar} is adequate to enhance the tidal deformability $\Lambda > 800$!

Self-Interactions of "natural" size provides adequate repulsion.

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)



Nelson, Reddy, Zhou (2018)

An, Pospelov, Pradler (2013)   Rrapaj and Reddy (2016)   Chang, Essig, McDermott (2017,2018)

Buschmann, Dessert, Foster, Long, Safdi (2021)

Kouvaris (2008) Baryakthar, Bramante, Li, Linden, Raj (2017). Chatterjee, Garani, Jain, Kanodia, Kumar, Vempati (2022)

Conclusions

Neutron stars are good places to look for dark matter. They accrete, trap, and produce it.

Neutron stars can constrain the particle nature of dark matter. Robust bounds on the neutron star radii and deformability help calibrate them for dark matter discovery.

Current generation GW detectors at design sensitivity are expected to detect neutron star mergers at a rate of a few 10s per year. A small fraction may be close by and GW170817-like.

3rd Generation GW detectors (Cosmic Explorer & Einstein Telescope) will provide a large data set. We can begin to start looking for needles in the haystack.

Constraints on thermal and transport properties inferred from galactic neutron stars and supernovae will likely improve with more observations and modeling.